Comparative Study of Biomass Yields for Tree and Grass Crops Grown for Conversion to Energy

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The following organizations cooperated with the Hawaiian Sugar Planters' Association and the Department of Business, Economic Development and Tourism to complete the project.

BIOENERGY DEVELOPMENT COMPANY

HORTICULTURE DEPARTMENT, UNIVERSITY OF HAWAII

AGRONOMY AND SOILS DEPARTMENT, UNIVERSITY OF HAWAII

FOREST SERVICE INSTITUTE OF PACIFIC ISLANDS FORESTRY

STATE DEPARTMENT OF LAND AND NATURAL RESOURCES, FORESTRY AND WILDLIFE DIVISION

UNITED STATES DEPARTMENT OF AGRICULTURE, SOIL CONSERVATION SERVICE, PLANT MATERIALS CENTER, MOLOKAI

HAWAII NATURAL ENERGY INSTITUTE

HAWAIIAN RESEARCH, LTD

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EXECUTIVE SUMMARY

This report summarizes a seven-year study of biomass production in five diverse Hawaii sites. The objectives of the work were to determine the species of trees adapted to the sites in small plot evaluation trials and to compare the productivity of recommended tree species with grasses in larger plot trials which would be more typical of a commercial operation. An economic analysis of biomass production was performed based on the biomass yields obtained. A third objective was added when we recognized the presence of individual elite trees in our small and large plot trials. These elite trees were selected and a few were propagated by means of conventional vegetative propagation and by micropropagation in sterile culture.

The small plot species trials indicated relatively good yield potential for *Eucalyptus* species, especially *E. grandis*, and *E. urophylla*, in the high rainfall sites of Kilohana, Kauai, Mountain View, Hawaii, and Honokaa, Hawaii. Both *Leucaena leucocephala* (K636) and *Casurina equisetifolia* were best adapted to the lowland, low rainfall sites.

The large plot trials confirmed the relatively good productivity of *Eucalyptus* species in high elevation sites and *Leucaena leucocephala* in low elevation sites. Trees averaged over all sites produced biomass at the rate of 9.2 t/a/yr compared to 13.8 t/a/yr for the grasses. The highest annual yield for a tree species was 14.2 t/a for *E. urophylla* at the Honokaa site. The highest yield for a grass species was 19.6 t/a/yr for napiergrass (banagrass) at the Hoolehua site. The grass species evaluated, sugarcane and napiergrass, yielded more biomass than the trees except for the Honokaa site.

At the Mountain View site we selected several elite individuals from the seedling tree populations in the small and large plots. These elite trees are being propagated for future comparison in yield tests. One selection designated as URO4 (*E. urophylla*) is currently being mass propagated, using micropropagation at the HSPA, for inclusion in a large trial to be conducted on the Hilo Coast.

Tree biomass could be produced for about $71/t at the Honakaa site and about $103/t at the Molokai site based on the yields obtained in the large demonstration plots. Irrigated napiergrass (banagrass) could be produced for about $72/t on Molokai and unirrigated sugarcane could be produced for about $77 per ton at the Honokaa site (**Table 20**).

We have concluded that at current fuel prices, it is not feasible to produce, deliver and process biomass fuels for production of electricity exclusively from either grasses or trees at a profit from either irrigated or unirrigated sites. Higher-value products including fuel alcohols, chemical feedstocks, paper pulp, manufactured lumber and veneer are more likely uses of biomass than combustion fuels; all of these require detailed economic analysis based on the latest technology.

The high biomass yields produced on Hawaii's sugar plantations are considered to be among the highest in the world and the cogeneration of energy for processing and the production of electricity have set the world's standard. We have concluded that the best biomass option for Hawaii is to continue to produce a higher-value product such as sugar and produce energy as a by-product. In the same regard, trees could be produced for manufactured lumber or veneer and the bark could be used as a source of fuel.

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INTRODUCTION

Biomass is often cited as having a good potential for supplementing Hawaii's importation of oil used for the generation of electricity and production of liquid fuel. In fact, Hawaii already has a prominent history of using biomass as fuel, having a higher biomass utilization for electricity generation as a percentage of total energy generated than any state. The primary source of biomass fuel in Hawaii is bagasse, the fiber remaining after the processing of sugarcane. Since bagasse is a by-product fuel having only minimal handling costs, it does not have to be transported and prepared before use. This would not be the case if biomass fuels were produced independently of a higher-value product such as sugar.

The continuation of biomass production for energy will, in part, require research to determine the best adapted crops for Hawaii's diverse environments. At the request of the Department of Business, Economic Development and Tourism (DBEDT) we have made a comparative study of the productivity of grass and tree crops in five diverse Hawaii locations to determine if production of biomass is feasible when independent of a host industry such as sugar processing.

Biomass

Biomass is considered an alternative to oil or coal as a fuel for the production of electricity. Usually biomass fuel results as a by-product of agricultural or forest crops grown for higher-value purpose; e.g., sugarcane is grown for its sugar and the fiberous residue, bagasse, is burned as a fuel. Likewise, trees are grown for high value pulp, veneer and the bark is burned as fuel. When both grass and tree biomass crops are burned, process steam and electricity are often cogenerated. Hawaiian sugar factories have set the world standard for cogeneration. Opportunities may also exist for the future conversion of grass and forest by-products to liquid fuels such as ethanol and methanol. One must be aware that there are no agricultural production harvesting or transportation costs associated with the production of either of these by-product biomass fuels. In contrast, biomass fuels grown specifically for fuel must bear all costs associated with their production, harvesting and transportation, and processing. Biomass fuels can be produced from grass crops such as sugarcane (*Saccharum spp.* hybrids) and napiergrass (*Pennisetum purpureum*) or from tree crops such as *Eucalyptus spp.* and *Leucaena spp.* Biomass in this report will refer to the above-ground dry matter produced by grasses or trees.

Residue Recovery

Crop residue recovery is an intermediate approach to biomass fuel production. Here, biomass is collected in the field after harvest with the agricultural costs charged to the higher-value primary crop; only collection, preparation, and transportation are charged to the biomass fuel. The field collection of sugarcane leaf trash and collection of orchard prunings are examples of residue recovery. In California substantial infrastructure has been developed to recover, process, and convert orchard prunings to energy. Sugarcane residue recovery from fields has been studied and there has been some commercial development in the Philippines. In Hawaii sugarcane leaf residue is harvested and milled with the sugarcane to provide additional energy.

Value of Agricultural Products

When growing biomass crops as fuel, consideration must be given to the traditional hierarchy of value of agricultural products. Food uses are usually highest in value, followed by feed, fiber, feedstock, and fuel. Unless the value of fuel is increased, it is unlikely that private investment will be used to grow crops specifically for energy production. This is especially true for Hawaii where land and production costs are considerably higher than other locations in the United States. Knowledge of the yield potential of candidate biomass crops in diverse environments is essential information for consideration of commercial biomass ventures.

The purpose of this study was to compare the productivity of grass and tree crops in five diverse Hawaiian locations, and to determine the economic potential of growing biomass for energy independent of a supporting industry such as sugar or higher-value wood products.

LITERATURE REVIEW

The sugar industry initially burned mixtures of wood as whole logs and bagasse to power the sugar mills, but the introduction of grate furnaces about 1900, precluded the continued use of wood (Hilton and Hoskins, 1985). Process steam for operating the sugar mill and a small amount of electricity were produced in the early inefficient sugar industry bagasse boilers. Later, upgraded boilers allowed substantial production of electricity and the opportunity to export to the public grid. By 1987, electrical power supplied by the sugar industry was 819,000,000 kWh or 8.7 percent of the total power generated (Kinoshita, 1984). Biomass generation accounted for 507,000,000 kWh or 5.3 percent of the total power generated in 1991, deferring the purchase of 2,000,000 bbl of oil, equivalent worth $45,000,000. Currently, Hawaii uses the highest percentage of biomass for electrical generation in the United States. In California, for example, only 0.3 percent of the power is generated from biomass (McMullin, 1991). Bagasse and macadamia nut shells are the only significant sources of biomass used for electrical generation in Hawaii. Potential sources of biomass crops include other grasses, such as napiergrass and sweet sorghum, and trees, such as *Eucalyptus spp.* and *Leucaena spp.* Municipal waste including a biomass component is currently being burned to produce electricity in Honolulu.

Grass Biomass

Grasses, such as sugarcane, napiergrass, and sweet sorghum, have been studied extensively as biomass energy crops. Alexander (1985) proposed the name "Energy Cane" to describe sugarcane hybrids selected for higher fiber and grown for their energy value. He reviewed the potential for utilizing grasses for energy and classified them as short, intermediate, and long cycle crops. Typical short-cycle grasses harvested at 4 to 5 months include maize, sorghum, and sudangrass; intermediate-cycle grasses harvested at 6 to 12 months include sweet sorghum and napiergrass, and long-cycle grass harvested at 12 months or longer include the sugarcane species hybrids. Typical yields of grasses grown in experimental plots in the three categories are given in **Table 1**. These yields are in some cases far in excess of commercial yields and should be considered here for comparative purposes only.

The commercial sugarcane crop in Hawaii provides about 15 t/a/yr (average for 1986-1991) of recovered dry biomass including sugar, bagasse and molasses solids. Actual biomass yield is higher by about 30 percent, but it is either burned in the preharvest cane fire or is lost in the sugarcane harvest, transport, and milling operations. The commercial yields of Hawaiian sugarcane are among the highest in the world.

Modern sugarcane cultivars are selected for high sugar production; it is expected that if selection were made for high fiber cultivars and if the agronomic practices favored high biomass yield, much higher yields could be obtained. Calvin (1976) considered sugarcane to have the highest potential of any crop to produce biomass per unit area with many advantages over other crops, such as regrowth after harvest (ratooning). Other grasses, notably napiergrass and sweet sorghum are also high yielding and offer potential as biomass grass crops. Mishoe et al. (1979) developed a model for optimum biomass recovery from sugarcane and reported that for Florida conditions a twice per year harvest gave the highest yield. This would not be expected in Hawaii where the sugarcane cultivars are selected for harvest at two years after planting.

Table 1. Grass biomass yield potential from experimental plots.

Crop	Dry Matter Yield t/a/yr	Location	Reference
Short Cycle (3 to 5 months)			
Sorghum/sudangrass	16.8	Hawaii	Unpublished
Maize	22.8 to 27.6	Hawaii	Unpublished
Forage sorghum	20.4	Hawaii	Unpublished
Intermediate Cycle (6 to 11 months)			
Sweet sorghum	43.2	Louisiana	Giamala et al., 1984
Napiergrass (banagrass)	19.2 to 43.2	Hawaii	Wu & Tu, 1988
Napiergrass	26.4	Puerto Rico	Alexander, 1985
Sweet sorghum	27.6	Hawaii	Ginoza, 1982
Napiergrass	16.2-20.2	Florida	Striker et al., 1993
Long cycle (12 months)			
Sugarcane spp. hybrids	24.5 (burned)	Hawaii	Anders, 1989
Sugarcane spp. hybrids	28.8 to 50.4 (unburned)	Puerto Rico	Alexander, 1985
Sugarcane spp. hybrids	26.4 (unburned)	Hawaii	Wu & Tew, 1989
Sugarcane spp. hybrids	28.8 (unburned)	Louisiana	Giamala et al., 1984
Sugarcane spp. hybrids	19-25.1 (unburned)	Florida	Striker et al., 1993

Tree Biomass

Short rotation intensively cultivated (SRIC) trees also provide a potential source of renewable biomass; however, trees will require productivity gains similar to those that have been put in place for agricultural crops including improved germplasm, and cultural practices such as irrigation, fertilization, timely weed control, and optimum density planting. Trees planted as bioenergy crops will require substantial agricultural inputs not required in traditional forestry operations. High yield biomass operations have been established in the Tropics as demonstrated by Aracruz Cellulose Company in Brazil at Aracruz. *Eucalyptus* production was substantially improved by selecting high yielding cultivars and capturing the yield potential through the use of vegetative propagation (Campinhos,1984). Yield gains of about 165% were reported when selected clones replaced the planting of seedling *Eucalyptus*. Average dry matter yields of 6.8 t/a/yr were reported for seedling populations; the average yield for selected clones in experimental plots was 18 t/a/yr. Breeding and selection of trees from a diverse genetic base offers further opportunity for yield improvement.

Tree biomass yield data are not as readily available as for grasses. Yields for trees are often given in terms of volume without reference to density and it is often not clear if the data are based on dry matter or fresh weight.

A series of well designed yield trials was a component of the BioEnergy Development Corporation project on the island of Hawaii. *Eucalyptus grandis* averaged 9.9 t/a/yr when grown on a five or six year rotation in the Pepeekeo region of the Island of Hawaii. Mixtures of *Eucalyptus* (34%) and Albizia (66%) produced 13.6 t/a/yr on the same rotations. A seven-year rotation with this mixture gave 14.9 t/a/yr. Biomass yields from other locations on the island of Hawaii have ranged from 6.6 to 13.3 t/a/yr under various conditions of growth spacing and fertilization. *Leucaena leucocephala* cultivars (haole koa) yield from Waimanalo on the island of Oahu ranged from 3.2 to 21.7 t/a/yr under different ages, spacing, and cultural conditions Brewbaker (1980). The highest yields were obtained during the shortest rotations and where *Leucaena* selections having higher yield potential were selected. Kinch and Ripperton (1962) and Evensen (1984) also reported on the yield potential of Leucaena. In the Kinch study, conducted with inadequate irrigation during the summer months, *Leucaena* cut on a 2.5 month cycle for forage produced about 7.5 t of dry matter per acre per year. In the Evenson study conducted with adequate irrigation, the annual yield of dry matter was about 13 t/a/yr. Breeding work is now underway at the University of Hawaii to further improve *Leucaena* yield.

Objectives

The present study was designed to determine the relative yield potential of trees and grasses in five diverse Hawaii locations and to make a preliminary economic assessment of commercial production.

EXPERIMENTAL METHODS

Site Descriptions

Experimental plantings of potential biomass crops were made at five sites on four of the Hawaiian islands (**Photo 1**). The locations were: Mountain View, a wet, upland site on the Island of Hawaii; Honokaa, a drier, upland site on Hawaii; Puunene, a dry, irrigated, lowland site on Maui; Hoolehua, a dry, irrigated, intermediate elevation site on Molokai; and Kilohana, a wet, intermediate elevation site on Kauai. The sites represent a wide range of conditions for land potentially available for commercial biomass operations (**Tables 2 and 3**).

Table 2. Description of biomass production sites.

Site	Elevation (ft)	Annual Rainfall (in)	Average Temperature (deg F)	Radiation (Langleys)
Mountain View	972	182	70	311
Puunene	25	19.2	76.6	491
Kilohana	842	119.2	68.8	450
Hoolehua	250	28	73.4	450
Honokaa	762	81.2	70.2	390

Table 3. Description of soils at biomass production sites.

Site	Soil Series	Soil Type
Mountain View Hawaii	Keaukaha ext, rocky muck	Lithic tropofolists dysic isohyperthermic
Puunene Maui	Molokai silty clay loam	Typic torrox clayey Kaolinitic isohyperthermic
Kilohana Kauai	Halii gravelly silty clay	Typic gibbsihumax clayey ferritic isothermic
Hoolehua Molokai	Holomua silty loam	Typic torrox clayey kaolinitic isohyperthermic
Honokaa Hawaii	Paauhau silty clay loam	Hydric dystrandepts thixotropic isothermic

Experimental Designs

Two types of experiments were installed at each site: (1) a small plot replicated trial (comparisons were made of promising tree species grown at 1 x 1m (3.28 x 3.28 ft) spacing), and (2) a large plot replicated demonstration trial (trees were planted at 2 x 2m (6.56 x 6.56 ft) commercial-type spacing). A grass biomass plot was established at each site for comparison.

The trees were either propagated from seed by HSPA personnel or were obtained from the state tree nursery at Waimea, Hawaii. Plants were grown out in the nursery facilities of BioEnergy

Development Corporation at Pepeekeo, Hawaii, or at Maunawili, Oahu. Trees were grown in forestry dibble tubes and were planted in the field using a dibble bar to prepare the hole.

SMALL PLOT TRIALS

A core replicated group of three species was planted in the small plots. These were: *Casurina equisetifolia* Forst. & Forst, *Eucalyptus grandis* Hill ex Maiden, and *Leucaena leucoceplala* (Lam.) de Wit. These species were augmented with unreplicated plots of five additional species differing according to site characteristics. The core species were replicated four times at each site. The unreplicated augmented species were chosen from the following list:

SPECIES	SEED SOURCE
Acacia mangium	NFTA
Acacia mearnsii	NFTA
Casurina cunninghamiana	HDF
Casurina equisetifolia	HDF
Eucalyptus alba	BDC
Eucalyptus camaldulensis	BDC
Eucalyptus citridora	HDF
Eucaluptus robusta	HDF
Eucalyptus saligna	HDF
Eucaluptus urophylla	BDC
Leucaena diversifolia K156	UH
Leucaena leucocephala K636	UH
Leucaena leucocephala X *L. diversifolia* K743	UH

BDC— BioEnergy Development Corp.
HDF— State Dept. of Forestry
NFTA— Nitrogen Fixing Tree Association
UH— University of Hawaii (Horticulture)

Depending upon the condition of the field, different techniques were required for site preparation. The Mountain View site was prepared by crushing the existing ratoon cane with a Krajewski disk (sugar factory mill roll) **Photo 2**. This was the only operation necessary in this rocky site with little soil. The trees were planted directly into the mulch provided by the crushing operation (Photo 3). At the other sites, preparation operations similar to those used for sugarcane were used. Fields were plowed and disked to prepare the seedbed for planting.

Stand

Trees were established in $100m^2$ (1076 ft^2) plots consisting of ten rows of ten trees planted at 1 by 1 m (3.25 x 3.25ft) spacing giving a population of 10,000 trees/ha (4,048 per acre), except on Maui where the constraints of the furrow-irrigation system allowed a spacing of 1 by 1.5 m (3.25 x 4.87ft) and a density of 5,988 trees/ha (2,424per acre).

Weed Control

Weeds have a serious impact on the growth and development of trees. A considerable effort was made to control weeds at the sites. At Mountain View, a rocky site, a crushing roller pulled behind a D8 tractor was used to prepare the seedbed. The roller accomplished the task of reducing a volunteer ratoon crop of sugarcane to a mat which provided a water-preserving mulch for the transplanted trees **(Photo 3)**. The mulch also provided initial protection from weeds. Preplant applications of Roundup (glyphosate) and Princep (simazine) were applied followed by postplant applications of Goal (oxyfluorfen) and Fusilade (fluazifop) to maintain control. Some hand weeding was done at the Kilohana site for the removal of California grass (*Panicum purpuresens*). Spot spraying with Roundup was necessary at some sites.

Fertilizer

Fertilizer containing 14 percent each of N, P_2O_5 and K_2O was applied at the rate of 1.67 oz per tree (423lb/a) at planting. An additional 1.67 oz of fertilizer per tree was applied at 6 months, 12 months and 18 months after planting. Nitrogen, potassium, and phosphorus were applied at 236lb/a over the course of the experiment. At the Puunene site, a single application of fertilizer was made at planting since the mill wastewater used for irrigation was nutrient rich.

Irrigation

Irrigation was required at the Puunene, Maui, site and the Hoolehua, Molokai, site. Wastewater from the sugar mill was used at the Maui site and mountain water from the Molokai irrigation system was used at the Molokai site. No method was available to measure the water applied to the plots at either location. Irrigation was applied daily through a drip irrigation system on Molokai and on a two-week to one-month interval through furrows on Maui depending on the time of year **(Photos 4 through 8)**.

Data Collection

Tree heights from the ground to the tip of the tallest shoot were measured at 3, 6, 9, 18, and 24 months and diameter at 4.3 ft height was measured at 12, 18, and 24 months. Measurements were collected systematically from 20 sample trees per plot in the same order at each measuring date. The Mountain View and Kilohana sites were destructively harvested at two years for biomass determination.

Allometric equations for estimating biomass were developed for the Mountain View and Kilohana sites. Mean annual increments in biomass were estimated using the equations.

LARGE DEMONSTRATION PLOTS

To determine yield potential, on a scale closer to commercial practice, larger plots are required. At each of the five sites, we established three tree species considered to have the best commercial potential in one acre plots. There were three replicates of each species in each location.

Soil Preparation

See description for small plots.

Stand

Trees were planted at 2 x 2 m(6.5 x 6.5 ft) spacing (Photo 11), giving a density of 2,500 trees/ha (1,012 per acre) which was one-fourth the planting density of the small plots. The 2 x 2 m spacing has been suggested as a practical planting arrangement for commercial plantings in Hawaii. Spacing in the Maui test deviated from the other tests owing to the constraints of the furrow irrigation system. On Maui, the spacing was 2 x 1.5 m giving 2,900 plants/ha (1,174 per acre).

Weed Control

The weed control practices employed were the same as those used in the small plots with the exception of Kilohana where more attention was given to weed control in the small plots.

Fertilizer

The trees were fertilized at the same rate per tree as in the small plots, but owing to the lower population the amount of fertilizer applied per acre was less. At planting, fertilizer having 16 percent each of N, P_2O_5, and K_2O was applied at 1.7 oz/tree. Three additional applications were made at 1.7 oz/ tree. Nitrogen, P_2O_5, and K_2O were applied at 69 lb/a. At the Puunene site, application was made only at planting since the mill wastewater applied to the fields was nutrient rich.

Irrigation

Irrigation was required only at the Puunene, Maui, and the Hoolehua, Molokai, sites. The Maui site was furrow irrigated with mill wastewater and the Hoolehua site was drip irrigated with mountain water from the Molokai irrigation system. The amount of water applied to the plots was not measured. Irrigation was applied daily at the Molokai site and every two to four weeks at the Maui site except for periods of extended rainfall.

Data Collection

Tree diameter data were taken in each plot at 24, 36, 48, and 60 months after planting. We determined from the small plot experiments that collection of the height data was not necessary for prediction of biomass; therefore, it was not collected in the large demonstration plots. A nondestructive random line technique was employed in the data collection. At the 60-month harvest, 20 randomly selected trees per species per replication were felled and measured. Samples were taken of the wood from individual trees for moisture determination. Tree mortality data were collected to calculate a final stand.

Data in both the small plot tests and the large demonstration plots were analyzed by analysis of variance. Regression analysis was used for developing the allometric biomass equation. **Photos 9, 10, 13, 18, 19 and 20** show tree stands at several of the sites at various times after planting.

Grass Planting

Sugarcane was planted at all sites except for Molokai where napiergrass 'banagrass' was planted (**Photo 12**). Plots of 0.4 ha were established. At each site, standard procedures for planting and culture of sugarcane were followed. Cultivars recommended for the location were planted. Cultivar 68-1158 was used at Mountain View and at Kilohana, H73-6110 was planted at Puunene, and H65-7052 was used at Honokaa. The sugarcane was harvested several times over the course of the experiment and the regrowth from harvested stools (ratoons)was used to reestablish the crop; only one grass crop was planted to obtain the biomass reported. Yields of biomass obtained in the grass plots were compared to yields obtained in the small and large plot tree trials. Photo 15, 17,18 and 21 show banagrass operations from planting to harvest on Molokai .

RESULTS

Small Plot Species Trials

Diameter and Height Growth:

In the two-year small plot trials at two years after planting, *Eucalyptus grandis* was the most productive of the replicated tree species at all sites, growing to an average height of 8.7 m (28.5 ft) and an average diameter of 6.6 cm(2.59 in) (**Tables 4 and 5, Figures 1 through 10**). At Kilohana, *E. grandis* grew to 10.8 m (35.4 ft) and attained a diameter of 6.6 cm (2.59 in). Mortality for *E. grandis* was highest at Puunene, where over-irrigation with mill effluent reduced growth potential and promoted parasitism by fungi. *E. grandis* is reported to be adversely affected by poor drainage and this was confirmed at the Puunene site. *Leucaena leucocephala* and *Casurina equisetifolia* growth was poor in the upland sites but good in lowland sites. Eucalyptus productivity was severely affected by lack of nutrient in upland sites. A check plot without fertilizer is shown in **Photo 22**.

Biomass Production

Biomass yield was measured for all species at two years at the Mountain View and Kilohana sites (**Table 6 and photos 23 and 24**). Of the replicated core species, *E. grandis* was the highest yielding at the Mountain View site (13.5 t/a/yr); *E. urophylla* was the highest yielding of the augmented species (16.1 t/a/yr). At the Kilohana site *E. grandis* was the highest yielding of the core species (18.3 t/a/yr) and *Acacia mearnsii* was the highest yielding of the augmented species. *E. urophylla* produced 21.2 t/a/yr at Kilohana.

The high yields of biomass at two years reflect the high population density of 10,000 plants/ha (4,048 per acre) and high fertilizer use on a per hectare basis. The exceptionally high yield of 22.9 t/a/yr at Kilohana with *Acacia mearnsii* is of great interest and this species should be evaluated in future experiments. Of the *Eucaluptus* species evaluated, *E. urophylla* appeared to have the highest potential for high density short-term plantings. This, combined with its known ability to coppice, makes this species a good candidate for biomass planting. Average survival rates were the highest at two years for *E. grandis* (93%). The poorest survival was recorded for *Acacia mangium* (67%) (**Table 7**).

Species such as *Leucaena leucocephala* will require protection from grazing cattle. Plots of *Leucaena* were selectively grazed at the Kilohana site resulting in loss of the plots.

Poor drainage at the Puunene site reduced tree growth. The potential for production at this site is much greater than achieved. To achieve higher production, more control over the irrigation amounts and timing are required. Drip irrigation with improved drip tubes would provide this control and result in higher yield. Higher yield potential also exists for the Hoolehua site and this can be achieved by use of a better designed irrigation system and by searching for species better adapted to the site.

Equations

Allometric equations for predicting dry biomass at two years were fitted from the Mountain View tree diameter and harvest data (Table 8). The equations had the form $B=aD^b$ where the total above ground biomass (a) is a correction factor calculated as $EXP(c+s_{y.x}{}^2/2)$ and (b) is the slope of the regression. The constant term (c) for the regression and $s_{y.x}$ is the standard error of the estimate of the regression. The r^2 for the equations varied from 0.89 for *Leucaena leucocephala* to 0.98 for *Eucalyptus robusta* **(Table 9)**. The equations were tested using data sets from both Mountain View and Kilohana. The prediction of biomass based on tree diameter varied from zero percent for *Acacia mangium* to 8.8 percent for *Leucaena leucocephala* at the Mountain View site (Table 10). When the Mountain View-derived equations were applied at the Kilohana site, the variation was -19.2 percent for *A. mangium* and -2.3 percent for *Eucalyptus urophylla.* A publication was prepared on the development of the equations.

Large Plot Demonstration Trials

The primary objective of the research was to determine the biomass yields of trees planted at 6.5 x 6.5 ft (1,031 plants/a) at five years. Tree diameter over the course of the trials was used as an estimator of growth. Growth in diameter was measured from 24 months to harvest **(Table 12 and Figs. 11 to 15)**. The *Eucalyptus* species, *E. grandis, E. saligna* and *E. urophylla*, produced their greatest diameter growth at the Hamakua site. *Leucaena leucocephala* produced about equal diameter growth at the low elevation, Puunene and Hoolehua sites. *Leucaena leucocephala* 'K636' is not adapted to the upland sites and was not planted. *Casurina equisetifolia* increased in diameter slowly at the upland Kilohana site and more rapidly at the low elevation, Hoolehua and Puunene sites **(Figures 11 through 15)**.

The trees were felled at five years for determination of biomass **(Table 13)**. The highest biomass yield was obtained at the Hamakua site with *Eucalyptus urophylla* (14.2 t/a/yr). *E. grandis* produced 13 t/a/yr. **Photos 25 through 30** show the harvest and measurement technique. Across all experiments *E. urophylla* and *E. grandis* produced about the same yield in upland sites. In the lowland sites *L. leucocephala* produced more biomass than either *Eucalyptus* or *Casurina.* The average yield of *Leucaena* at the Hoolehua and Puunene sites was 10.2 t/a/yr.

Table 4. Height measurements for tree species in five sites.

Species	Mt. View	Honokaa	Puunene	Hoolehua	Kilohana
	Height (ft)				
E. grandis					
3 months	3.2	2.7	2.3	0.6	3.6
6	6.1	---	---	3.6	---
9	10.3	---	---	4.7	9.3
12	16.1	17.4	12.7	12.8	19.3
18	28.9	22	---	21	27.6
24	30.2	33.1	26.6	23.6	35.4
C. equisetifolia					
3 months	2.3	1.5	2.9	2.1	3.2
6	4	---	---	3.7	---
9	5.2	---	---	4.9	5.5
12	6.9	6.9	9.5	11.2	9.4
18	12.1	9.5	---	15.1	13.8
24	14.1	10.8	18.4	19.3	16.5
L. leucocephala K636					
3 months	1.8	1.8	2.6	1.1	---
6	4.4	---	---	1.9	---
9	4.9	---	---	3	---
12	9.5	10.8	12.8	11.8	---
24	16.4	20	22.6	20	---
E. urophylla					
3 months	3.5	2.2	---	---	4.2
6	7.9	---	---	---	---
9	11.3	---	---	---	9.8
12	16.7	15.4	---	---	19
18	25.9	20.3	---	---	25.9
24	28.9	29.2	---	---	33.1

Table 5. Diameter measurements for tree by species in five sites.

Species	Mt. View	Honokaa	Puunene	Hoolehua	Kilohana
			Site		
			Diameter (in)		
E. grandis					
12 months	1.3	1.3	0.9	1	1.6
18	2.1	2.1	---	1.7	2.1
24	2.2	2.3	2.4	1.7	2.6
C. equisetifolia					
12 months	0.5	0.4	0.9	0.9	0.7
18	0.9	0.8	---	1.3	1.1
24	1.0	0.8	1.81	1.4	1.3
L. leucocephala K636					
12 months	0.8	0.9	1.1	1.1	---
18	1	1.4	---	1.5	---
24	1.1	1.6	2	1.7	---
E. urophylla					
12 months	1.4	1.3	---	---	1.5
18	2.0	1.9	---	---	2.0
24	2.1	2.2	---	---	2.5

Table 6. Biomass yield for trees at the Mountain View and Kilohana sites at 24 months.

Species	Weight	Trees Surviving*	Total Yield	Dry Matter Yield
	lb/tree	(No.)	(t/a)	(t/a/yr)
Mountain View				
Acacia mangium	6.8	2,715	9.2	4.6
Acacia mearnsii	16	2,858	22.8	11.4
Casurina equisetifolia	6.4	3,046	11	5.4
Eucalyptus grandis	13.8	3,813	27	13.5
Eucalyptus urophylla	18.2	3,528	32.1	16.1
Leucaena leucocephala (K636)	5	3,821	9.5	4.8
Kilohana				
Acacia mangium	9.7	2,898	14	7
Acacia mearnsii	28.9	3,163	45.7	22.9
Casurina equisetifolia	8.6	3,150	13.5	6.8
Eucalyptus grandis	19.4	3,772	36.6	18.3
Eucalyptus urophylla	22	3,862	42.5	21.2

*4,048 trees planted per acre

Table 7. Tree survival rates at Mountain View and Kilohana sites at 24 months.

Species	Mountain View	Kilohana
	(%)	(%)
Acacia mangium	67	72
Acacia mearnsii	71	78
Eucalyptus grandis	94	93
Eucalyptus robusta	95	--
Eucalyptus saligna	91	--
Eucalyptus urophylla	87	95
Leucaena leucocephala (K636)	94	--

Table 8. Wood moisture and density.

Site	Genus Species	Wood Moisture (%)	Wood Sp. Gravity (g/cm^3)	(reference)
Mountain View	*Casurina equisetifolia*	46.06	0.53	1.0
Kilohana		46.58	0.53	
Mountain View	*Leucaena leucocephala* (K636)	45.81	0.50	0.52
Mountain View	*Eucalyptus grandis*	64.07*	0 .30*	
Kilohana		57.75*	0 .34*	
Mountain View	*Eucalyptus grandis*	60.65	0.34*	NA
Kilohana		59.06	0.37*	
Mountain View	*Acacia mangium*	62.51*	0.27	
Kilohana		59.57*	0.30	0.65
Mountain View	*Acacia mearnsii*	56.05	0.41	0.53
Kilohana		53.88	0.44	

*significantly different within speices, P = 0.05

Table 9. Prediction of biomass (B) at two years using diameter (D) at 1.3 meters above ground in an allometric equation.

Species	Biomass Equation	R^2
Acacia mangium	B= 0.0966 (D) 2.142	0.97
Acacia mearnsii	B= 0.639 (D) 2.729	0.97
Casurina equisetifolia	B= 0.1168 (D) 2.523	0.93
Eucalyptus grandis	B= 0.0700 (D) 2.438	0.94
Eucalyptus robusta	B= 0.0473 (D) 2.756	0.98
Eucalyptus saligna	B= 0.0871 (D) 2.443	0.96
Eucalyptus urophylla	B= .0750 (D) 2.534	0.98
Leucaena leucocephala	B= .1005 (D) 2.391	0.89

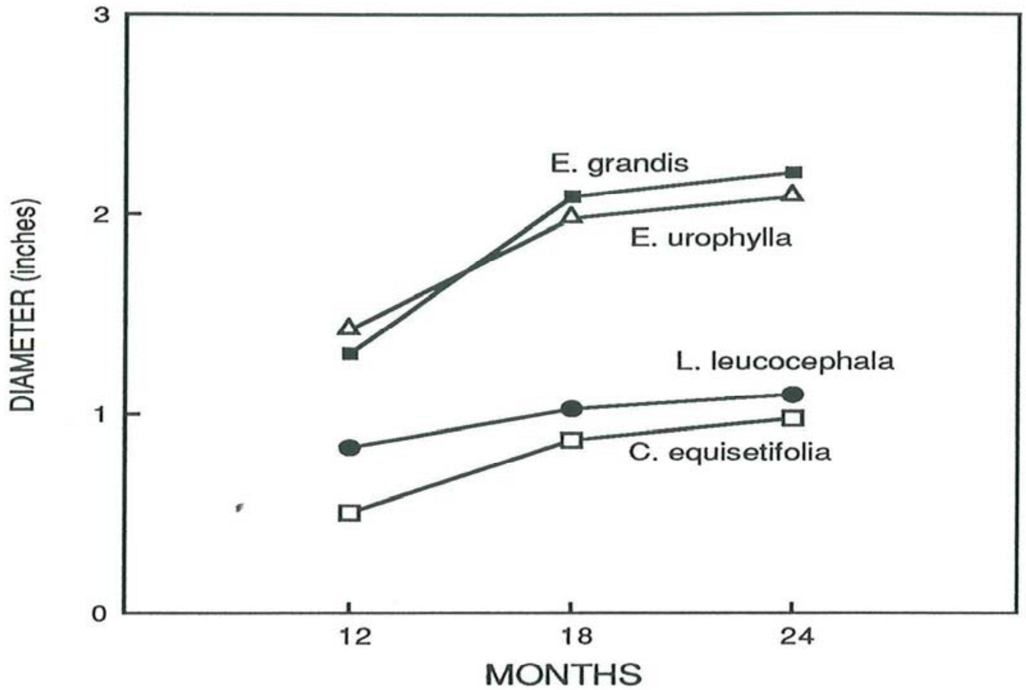

Figure 1. Diameter growth for trees at the Mountain View site.

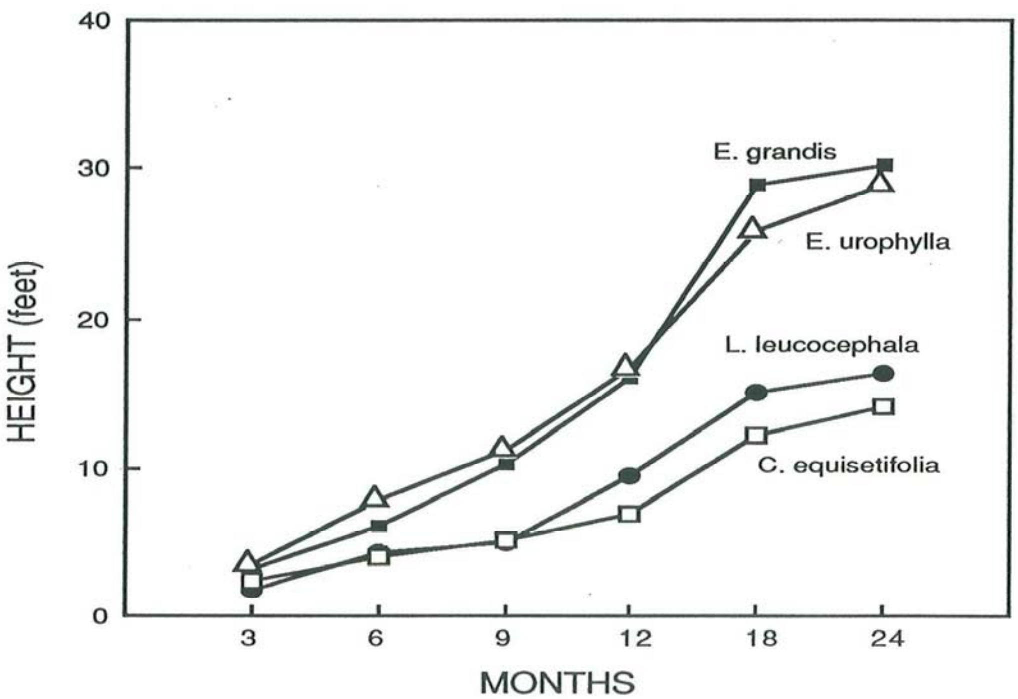

Figure 2. Height growth for trees at the Mountain View site.

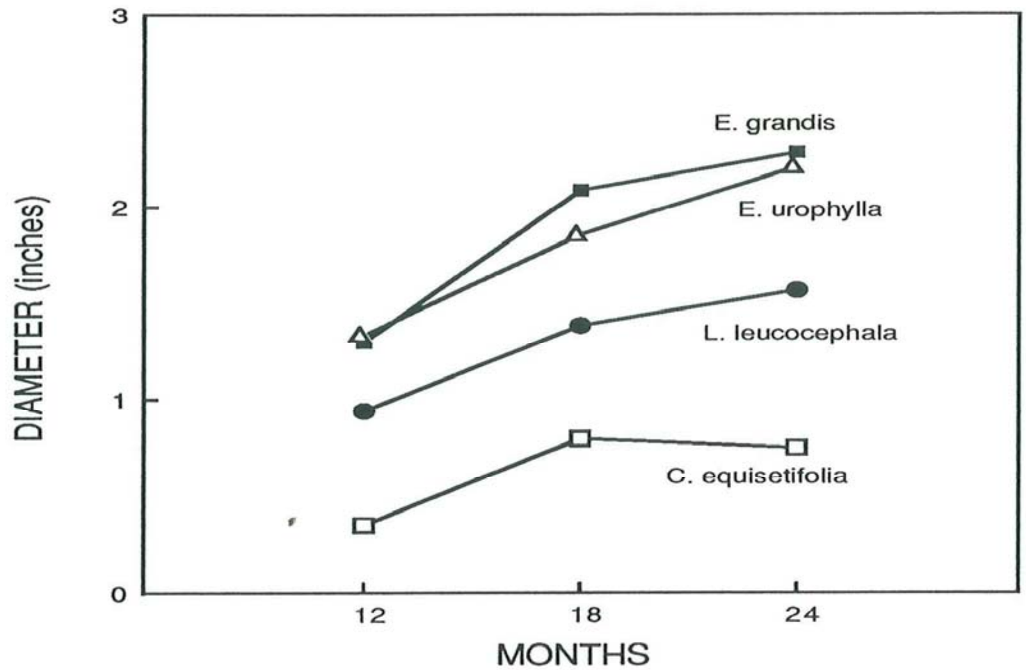

Figure 3. Diameter growth for trees at the Honokaa site.

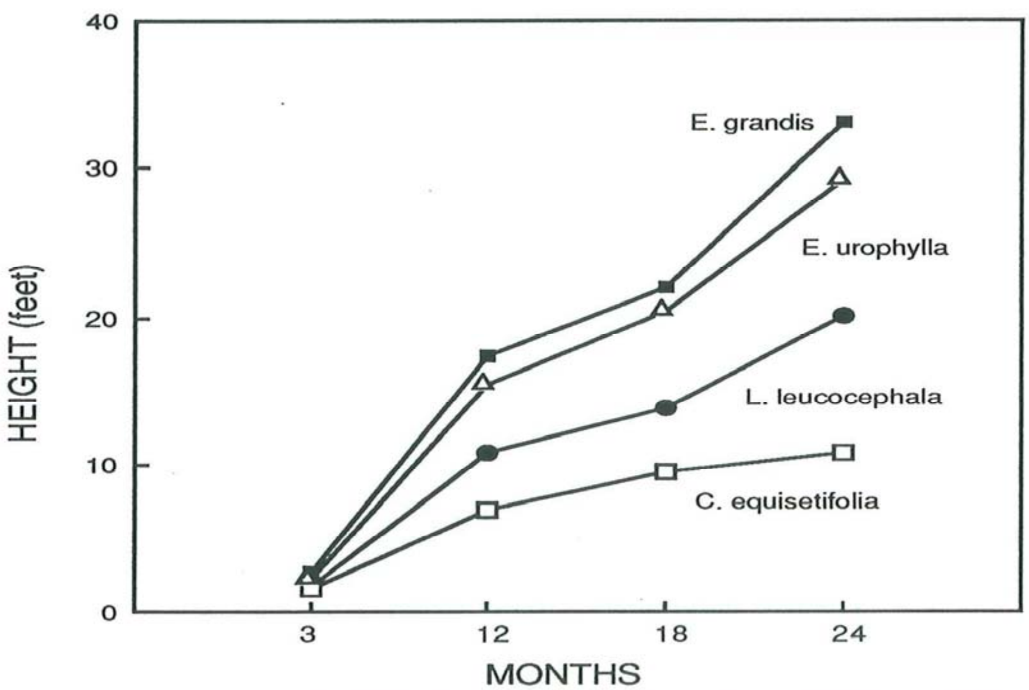

Figure 4. Height growth for trees at the Honokaa site.

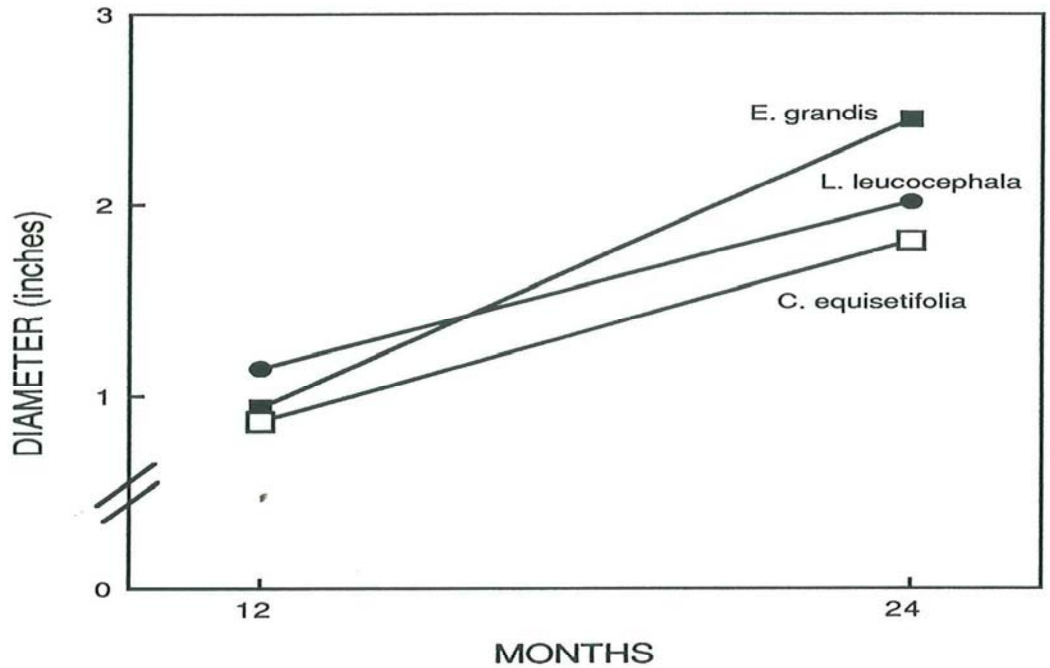

FIGURE 5. Diameter growth for trees at the Puunene site.

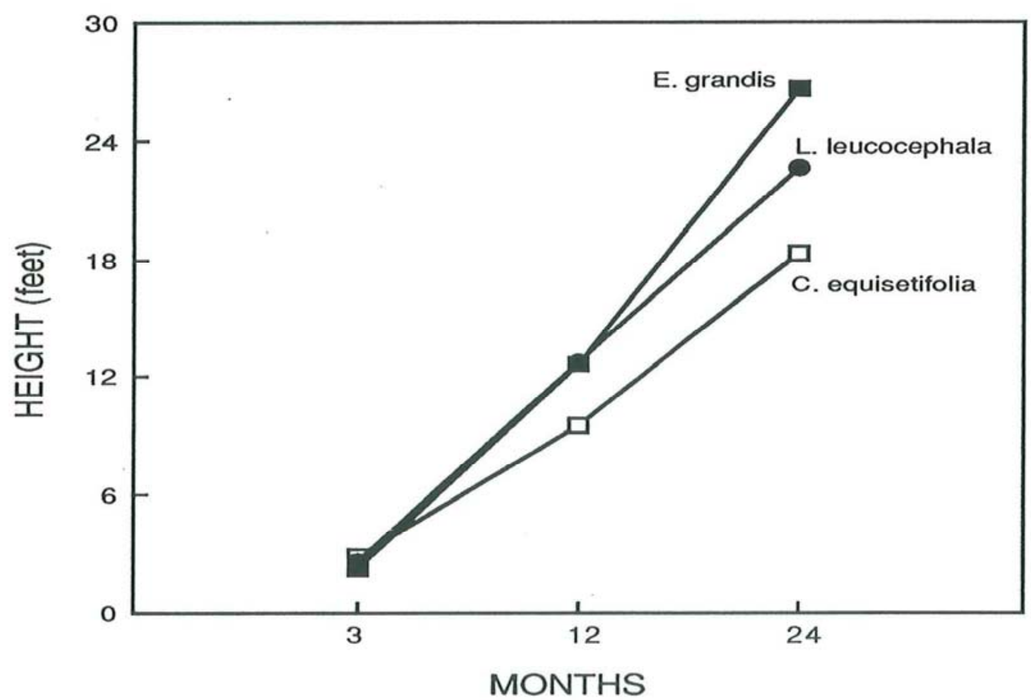

FIGURE 6. Height growth for trees at the Puunene site.

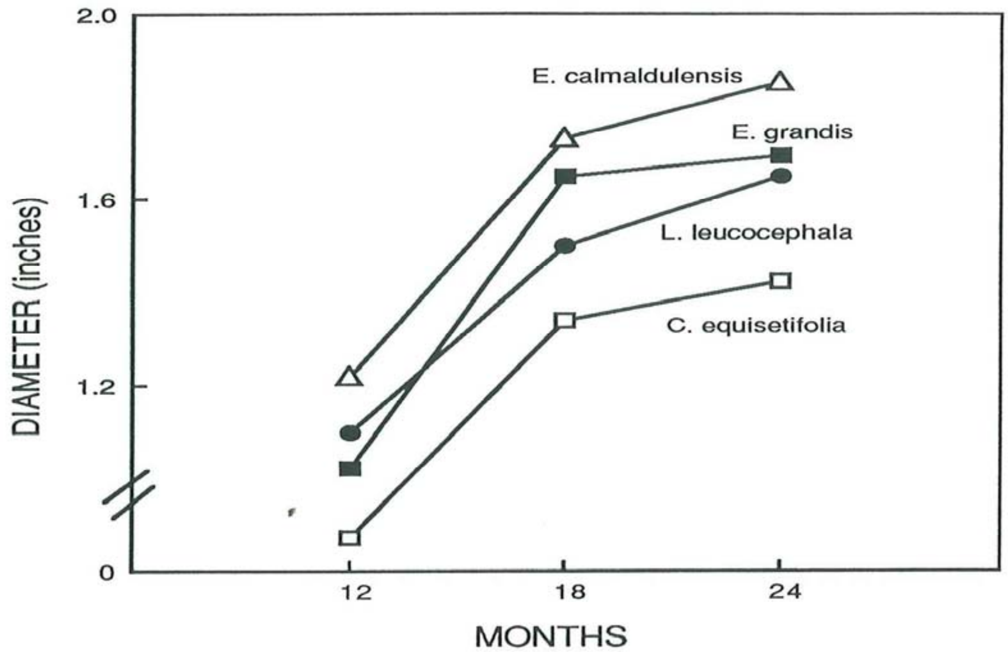

FIGURE 7. Diameter growth for trees at the Hoolehua site.

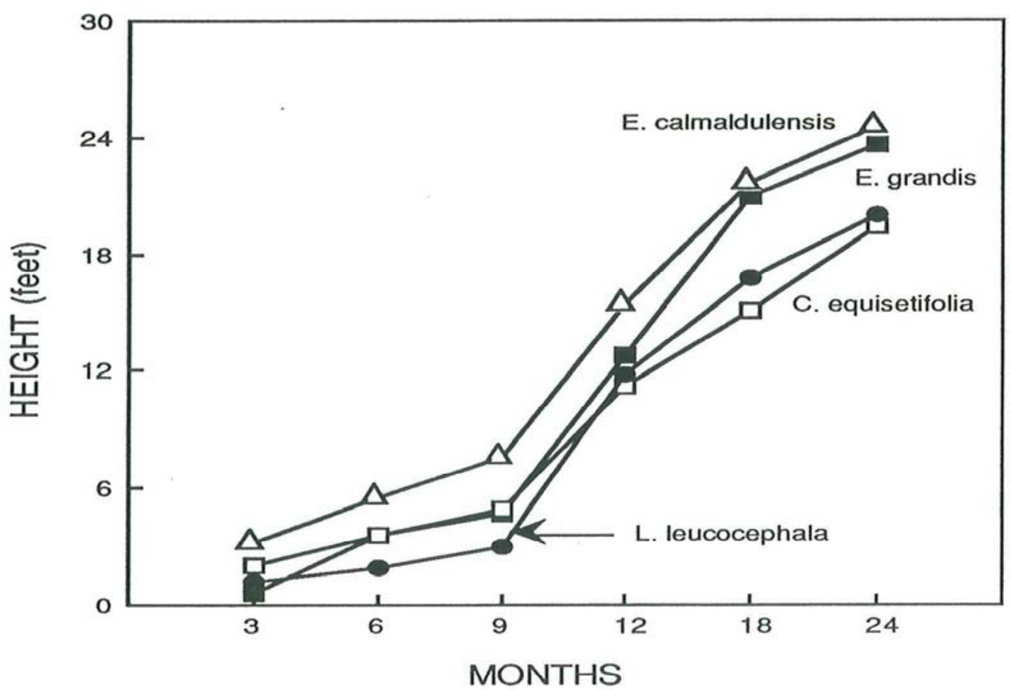

FIGURE 8. Height growth for trees at the Hoolehua site

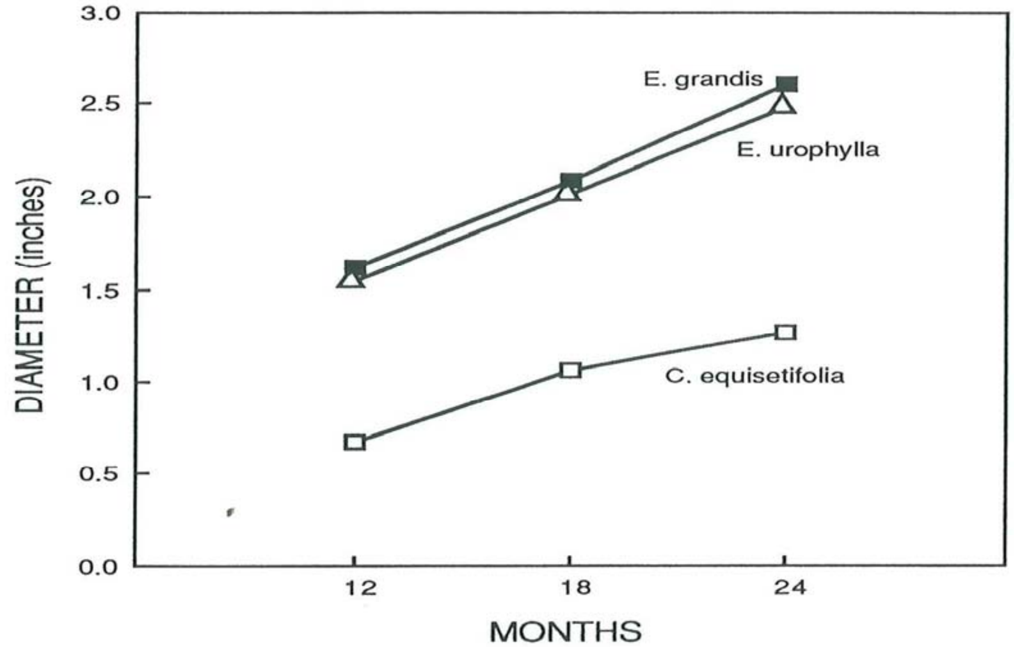

FIGURE 9. Diameter growth for trees at the Kilohana site.

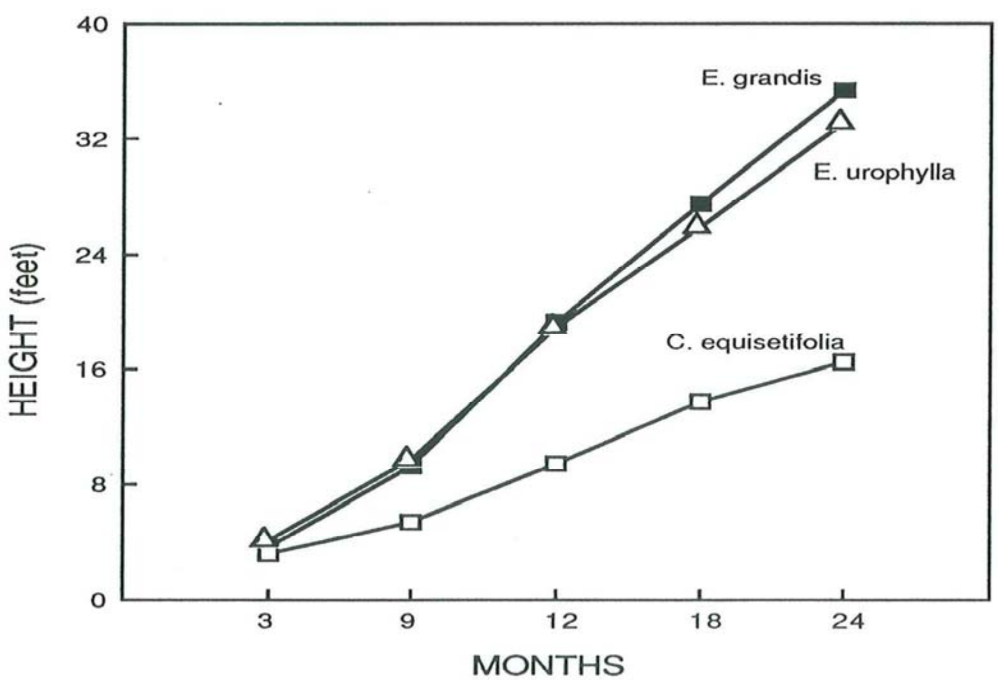

FIGURE 10. Height growth for trees at the Kilohana site

Table 10. Measured biomass compared to predicted biomass from the equations in Table 9.

Species	Measured Biomass	Estimated Biomass	Difference
	(lb/tree)		(%)
Mountain View			
Acacia mangium	5.92	5.90	0
Acacia mearnsii	16.83	16.74	0.53
Casurina equisetifolia	6.38	5.83	-8.6
Eucalyptus grandis	13.77	13.27	-3.7
Eucalyptus urophylla	17.56	17.36	-1.1
Leucaena leucocephala (K636)	4.97	4.53	-8.8
Kilohana (predictions using Mountain View equations)			
Acacia mangium	13.1	4.81	-19.2
Acacia mearnsii	24.79	26.77	+8
Casurina equisetifolia	8.65	7.63	-11.7
Eucalyptus grandis	24.24	20.66	-14.8
Eucalyptus urophylla	24.62	24.07	-2.3

Table 11. Mean dry matter increments at the Mountain View site based on allometric equations using diameter.

Species	12 months	18 months	24 months
	t/a/yr	t/a/yr	t/a/yr
Acacia mangium	1.03	2.11	2.61
Acacia mearnsii	4.18	11.47	9.13
Casurina equisetifolia	0.85	5.44	2.20
Eucalyptus grandis	5.44	11.34	10.26
Eucalyptus robusta	6.25	9.67	9.04
Eucalyptus saligna	6.21	8.91	8.95
Eucalyptus urophylla	7.42	11.92	10.98
Leucaena leucocephala (K636)	1.26	2.70	2.88

Table 12. Comparison of tree growth at five sites in large plot trials.

Site	Species	24	36	48	60
		Months			
		Diameter (in)			
Mountain View	*E. grandis*	2.2	3.3	3.9	4.6
	E. saligna	1.9	3.1	3.5	3.7
	E. urophylla	2.4	3.4	4.0	4.4
Hamakua	*E. grandis*	2.6	3.9	4.9	5.3
	E. saligna	2.5	3.5	4.4	4.5
	E. urophylla	2.6	3.9	4.9	5.2
Puunene	*C. equisetifolia*	1.8	3.0	3.2	3.2
	E. grandis	2.6	3.3	3.9	4.3
	L. leucocephala (K636)	2.4	3.3	4.1	3.9
Hoolehua	*E. camaldulensis*	2.4	3.2	3.5	3.9
	C. Equisetifolia	2.2	3.0	3.4	3.5
	L. leucocephala (K636)	2.5	3.4	3.8	3.9
Kilohana	*C. equisetifolia*	0.6	1.0	1.2	1.8
	E. grandis	2.3	3.2	3.6	4.2
	E. urophylla	2.5	3.4	4.2	4.6

The diameter data were plotted over the course of the experiment, Fig. 11 to 15.

The trees were felled at five years and biomass was determined for each species at each site, Table 13.

Table 13. Biomass yield potential for trees in five Hawaii sites at five years.

Site	Species	Planted Density Trees/a	Survival (%)	Annual Yield (t/a/yr)	Total Yield (t/a)
Mountain View	*E. grandis*	1,012	92	9.0	45.2
	E. saligna	1,012	86	5.0	25.0
	E. urophylla	1,012	94	9.0	45.0
Hamakua	*E. grandis*	1,012	86	13.0	65.0
	E. saligna	1,012	88	9.2	45.9
	E. urophylla	1,012	88	14.2	70.9
Puunene	*C. equisetifolia*	1,212	100	9.3	46.6
	E. grandis	1,212	80	7.4	37.1
	L. leucocephala (K636)	1,212	100	10.7	53.5
Hoolehua	*C. equisetifolia*	1,012	97	7.7	38.5
	E. calmaldulensis	1,012	92	4.4	21.8
	L. leucocephala (K636)	1,012	96	9.6	47.9
Kilohana	*C. equisetifolia*	1,012	92	2.2	11.0
	E. grandis	1,012	95	7.3	36.4
	E. urophylla	1,012	87	7.8	39.1

Table 14. Height, diameter, biomass per tree, and biomass per acre compared for five sites.

Site	Species	Dia. (in)	Ht (ft)	Biomass (lb/tree)	Biomass (t/a/yr)
Mountain View	*E. grandis*	4.6	57.1	259.6	9.06
	E. saligna	3.7	43.0	187.4	5.01
	E. urophylla	4.4	44.0	234.1	9.00
Honokaa	*E. grandis*	5.3	63.8	316.8	13.00
	E. saligna	4.5	50.8	266.9	9.16
	E. urophylla	5.2	60.4	367.6	14.18
Puunene	*C. equisetifolia*	3.2	36.8	126.5	9.35
	E. grandis *	4.2	43.1	165.4	7.46
	L. leucocephala	3.9	40.8	140.4	10.73
Hoolehua	*E. camaldulensis*	3.9	36.7	90.0	4.36
	C. equisetifolia	3.5	41.8	124.1	7.69
	L. leucocephala	3.9	42.4	151.4	9.59
Kilohana	*C. equisetifolia*	1.8	28.8	39.4	2.20
	E. grandis	4.2	40.2	174.2	7.27
	E. urophylla	4.7	44.0	188.1	7.81

*High mortality due to fungal rot in poorly drained site

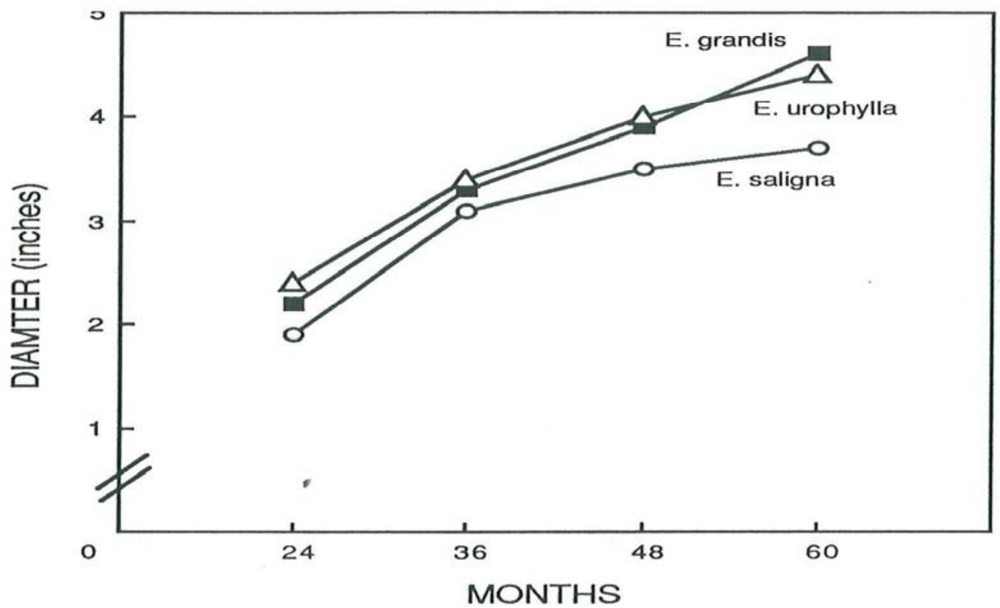

FIGURE 11. Diameter growth for trees in large plots at the Mountain View site.

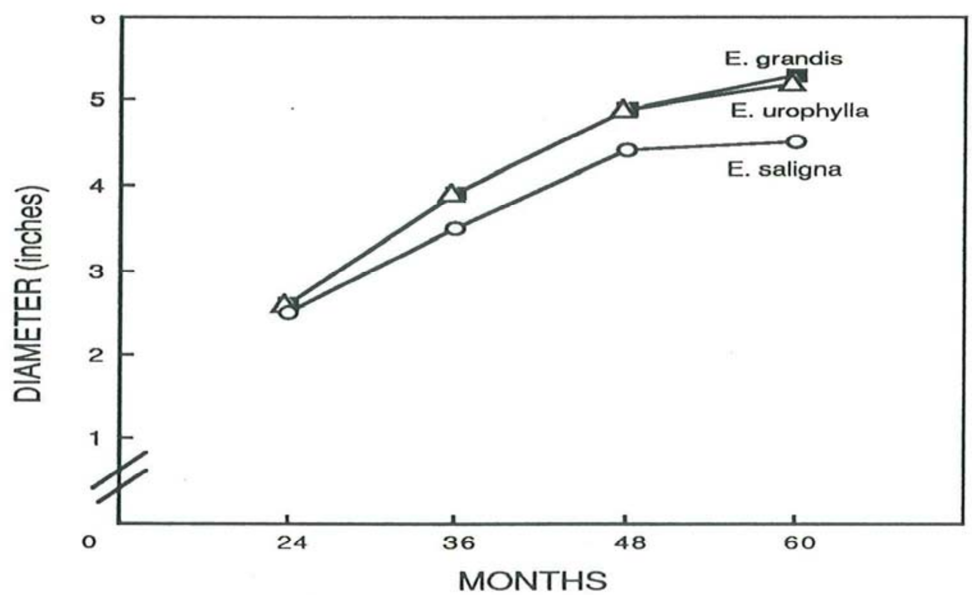

FIGURE 12. Diameter growth for trees in large plots at the Honokaa site.

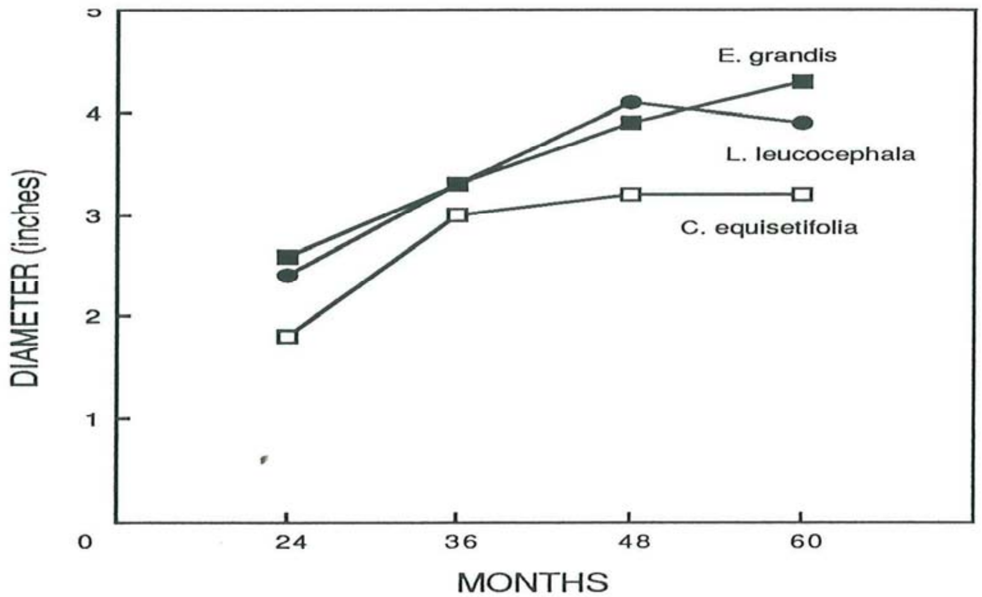

FIGURE 13. Diameter growth for trees in large plots at the Puunene site.

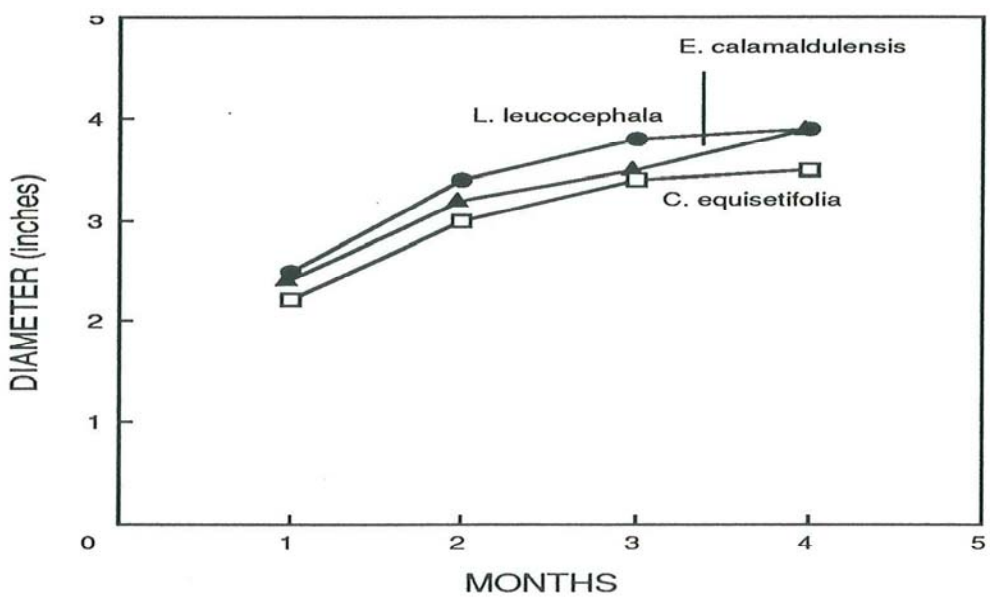

FIGURE 14. Diameter growth for trees in large plots at the Hoolehua site.

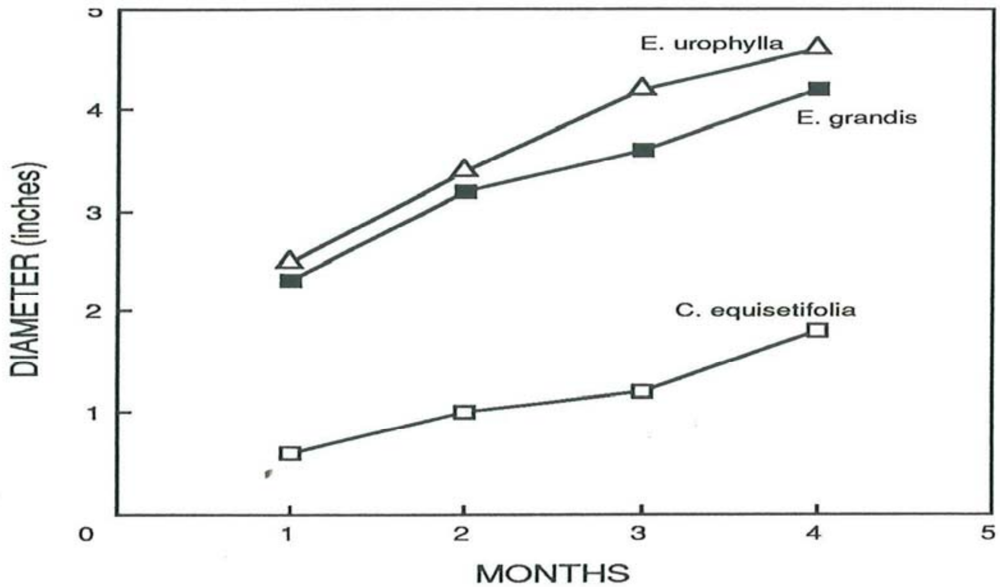

FIGURE 15. Diameter growth for trees in lagre plots at the Kilohana site.

Grass Biomass Yield

Grass yields are reported in **Table 15**. The highest yield obtained was at Hoolehua, Molokai, where 84.3 t/a were produced over a 4.3 year period. Problems with the harvest method and with irrigation at the Puunene site prevented the accurate estimation of sugarcane yield; therefore, the yields reported are based on the yield of commercial seed cane and dry weights of cane obtained in experimental harvests at the biomass site. Seed cane yields are expected to provide a good estimate of the yield of biomass from the site. The number of harvests ranged from four at Honokaa to seven at Hoolehua. The grass yields were low in the low sunlight higher elevation sites and higher in high sunlight low elevation sites. Commercial yields of both grasses and trees should be reduced by about 25% to reflect expected commercial yield.

Table 15. Grass Biomass Yields at Five Sites

Site	Grass	Harvest (no.)	Time (years)	Yield (t/acre)	Yield (t/a/yr)
Mountain View	Sugarcane	5	4.8	60.6	12.6
Kilohana	Sugarcane	4	4	51.3	12.8
Hoolehua	Napiergrass	7	4.3	84.3	19.6
Honokaa	Sugarcane	4	4.1	56.5	13.5
Puunene*	Sugarcane	NA	NA	NA	18.4

*Based on seed cane yields at HC&S Company and dry matter values obtained in cane harvested at the site. With the exception of the Honokaa site, the grass yields were higher than the tree yields when calculated on an annual basis.

Table 16. Grass and tree biomass yields compared.

Site	Highest Yielding Trees (t/a/yr)	Species	Grass Yield (t/a/yr)	Cultivar
Mountain View	9.0	*E. urophylla*	12.6	sugarcane, '68-1158'
Kilohana	7.8	*E. urophylla*	12.8	sugarcane, '68-1158'
Puunene	10.7	*L. leucocephala*, ('K636')	18.4	sugarcane, '73-6110'
Honokaa	14.2	*E. urophylla*	13.5	sugarcane, '65-7052'
Hoolehua	9.6	*L. leucocephala*, ('K636')	19.6	napiergrass 'banagrass'

EUCALYPTUS PROPAGATION

One of the constraints to commercialization of *Eucalyptus* trees for biomass energy or other uses is the rapid propagation of the selected clones. We stated in the previous section that there are no operational clones selected for commercial planting in Hawaii; but that efforts are being made to select and propagate clones with higher yield potential than the currently used seedling populations of *E. grandis* and *E. saligna*. BioEnergy Development personnel have selected 70 trees at about 10 years age from about 700 acres and the HSPA has selected additional trees from its small plots at the Mountain view site. Selected trees include *E. urophyla, E. grandis and E. robusta.* HSPA also obtained vegetative propagation material for two imported Brazilian clones from Aracruz Cellulose Co. designated as B1 (AR1186) and B2 (AR2277). The wood density of AR1186 and AR 2277 was 570 kg/m^3 and 667 kg/m^3 respectively as reported by Aracruz. Both cuttings and meristems were collected for conventional and micropropagation (**Photos 31 through 33**). The BioEnergy selections are awaiting felling and collection of propagation material from the regrowth. Earlier attempts to girdle the trees by BioEnergy personnel did not result in production of propagation material and felling will be the next procedure attempted. Some selections may not coppice (regrow) and these should not be selected for vegetative propagation.

The HSPA selections were made from two-year-old trees grown at Mountain View, Hawaii spaced at 2 x 2 m (6.56 x 6.56 ft). B1 and B2 were collected from the Puunene, Maui planting where they gave excellent growth as single tree plantings. The selected trees were felled and meristems obtained from the regrowth were placed into sterile culture according to methods developed by the HSPA (1989 Ann. Rep. p. 80). After establishment, the plantlets were maintained, divided and then placed on rooting media. Rooted plantlets were removed from the sterile culture media and placed in a humid environment until the formation of cuticular leaf wax. The lack of formation of leaf wax in culture makes the plants highly susceptible to desiccation upon removal to a less humid environment. The media used to maintain and multiply *Eucalyptus* included the following per liter:

Ingredient	Amount per liter
Sucrose	20g
Myoinsitol	100mg
Kinetin	0.2mg
BAP	0.5mg
Thiamine HCL	4mg
Ca panothenate	0.1mg
Biotin	0.1mg
Glycine	2mg
Riboflavin	1mg
Ph adjusted to 5.8	

The rooting media was prepared by modifying the multiplication media by removing BAP and kinetin and adding IBA at 1mgl-1.

Variation in the amount of sucrose, temperature and light all had dramatic effects on the growth of *Eucalyptus* in culture (Robert Harris, personal communication). Optimum rates of multiplication occurred in liquid medium with a sterile bridge while optimum rooting occurred in solid medium. Optimum light intensity was 184 micromoles/m^2 for multiplication and 91 micromoles/m^2 for rooting. Rooting was also improved by placing the cultures in complete darkness for 72 hours. The optimum temperature for growth was 30 C.

A high humidity chamber is required for removal of plants from culture. Misting should be tried to improve the survival rate.

The three HSPA Hawaii-selected trees and B1 from Brazil are being maintained in aseptic culture at the HSPA, Aiea. A few plants of *E. urophylla* No 4, *E. Grandis* No 1, *E. robusta* No 1 and B1 have been taken from culture and planted in the field at Maunawili on Oahu and at Pepeekeo on Hawaii (BioEnergy Development). At the Pepeekeo site the HSPA clones are being compared with several clones from Florida selected by Don Rockwood and supplied to the HSPA from Twyford Labs in California where the clones are maintained.

The HSPA clones, especially *E. urophylla* No 4, can be produced in large numbers through micropropagation from material already in culture. A project to carry out the propagation is presently under way and our goal is to produce 1000 trees of at least two HSPA clones and one Brazilian clone by mid-1994.

In addition, meristematic tissue will be harvested from a large number of selected trees from the BioEnergy program during 1993. This material will be placed into micropropagation and increased to several hundred trees each. The selected trees will be evaluated in plots for yield potential.

The inventory at HSPA in September 1993 was:

Clone	No of culture tubes	Estimated No. of Plants
B1 Aracruz 1186	10	100
B2 Aracruz 2277	120	1200
R1 HSPA *E. robusta*	16	160
G1 HSPA *E. grandis*	20	200
URO 4 HSPA E. *urophylla*	20	2000

An inventory of about 10,000 plants of URO 4 is currently being held at the HSPA (Nov. 1993). These will be placed in rooting media and then transferred to our nursery at Maunawili.

TREE IMPROVEMENT

Forestry research in Hawaii has traditionally been directed toward protection of watersheds from erosion and not toward the production of high yielding forests for commercial development. However, since 1982 the Department of Energy and others have funded a biomass for energy project on C. Brewer Co. land along the Hilo Coast. A subsidiary of C. Brewer Co. named BioEnergy Development Co. was formed which worked closely with the United States Forest Service to develop practices for the growing and harvesting of trees as a renewable biomass source of energy. About 700 acres of primarily *Eucalyptus* were planted in spacing, fertilizer and species evaluation trials. A report describing the results of this long-term program was recently published (Whitesell et.al.).

The *Eucalyptus* used in the BioEnergy plantings were propagated from seed and plot yields from the plantings have ranged from 8 to 12 ton/a/yr (Whitesell et al.).

There is considerable opportunity to increase *Eucalyptus* yield by both selection of elite types adapted to a particular environment and by breeding followed by vigorous selection for high yield and disease resistance in different environments. The clonal selection approach has led to large production gains in Brazil at the Aracruz Cellulose Co. (Ikemori and Campinhos, 1984) **(Photo 34 and 35)**. The average increase in production changed from $33m^3$/a/yr to $70m^3$/a/yr, an increase of 112 percent after the first clones were selected. Trees were selected for traits other than yield; one agronomic trait chosen was the ability to resprout (coppice) since the intent was to propagate the trees asexually. Trees selected at Arazruz were considered to be hybrids of *E. grandis and E. urophylla*. The vigor of the F1 hybrids was captured by clonal propagation.

Further gain can be made by introgression of traits from diverse sources of Eucalyptus by breeding. In Florida, tree volume increased by 163 percent from a base population after three generations of breeding and selection over a 20-year period (Leidig and Whitesell, 1992). Breeding and selection also produced higher *Eucalyptus* yields in China under the direction of Australian advisors at Dongmen. The crossing of *Eucalyptus* was in progress in Brazil in 1986 **(Photo 38)**.

Selection of elite *Eucalyptus* clones and breeding of elite types also has promise for improving *Eucalyptus* in Hawaii. A proposal for improving *Eucalyptus* in Hawaii was made by Leidig and Whitesell (1992). They proposed the importation of Australian provenances that have performed well in tests in Hawaii as described by Roger Skolmen (1986) and the selection of 120 elite trees from the BioEnergy Development plantings. They recommended that the selections be vegetatively propagated.

BioEnergy Development has recently selected 70 trees from their plantings on the Hilo Coast according to the recommendation of Leidig and Whitesell. These will be vegetatively propagated by conventional as well as micropropagation techniques. The trees will be planted in propagation blocks for production of additional vegetative cuttings and eventual planting in experimental plots and production blocks for evaluation. Several elite trees were also selected from the HSPA biomass trials **(Photo 36 and 37)**. The HSPA selections have been vegetatively propagated and have been planted in observation trials at Pepeekeo, Hawaii. Comparisons were made between these clones and several clones imported from Florida **(Table 17)**. Clones imported from Aracruz have been evaluated by BioEnergy Development Co. at the same location but in a separate experiment.

Elite seedling *Eucalyptus* provenances were also imported by the HSPA from the Dongmen project and were planted at Pepeekeo on the Hilo Coast. This material is now 2½ years old and was evaluated on March 23, 1993 **(Table 18)**. Many of the provenances in this study are vigorously growing and should be selected for elite types to be placed into vegetative propagation. Further reports on this trial will be made as it progresses.

Table 17. Height and diameter of clonal *Eucalyptus* at 15 and 22 month after transplanting at Pepeekeo, Hawaii.

Clone Designation		15 months		22 months	
		Height (feet)	Diameter (in)	Height (feet)	Diameter (in)
Twyford	2814 (Florida)	10.7	1.5	26.2	2.9
Twyford	Sampson (Florida)	3.4	0.2	failed	failed
Twyford	2805 (Florida)	10.3	1.3	25.6	2.6
Twyford	2798 (Florida)	4.6	0.3	failed	failed
HSPA	Uro 4 (Hawaii)	8.2	1.1	22.6	2.5
HSPA	Gra 1 (Hawaii)	8.9	1.0	25.6	2.8
HSPA	Rob 1 (Hawaii)	8.0	0.8	21.0	2.4

Table 18. Height and diameter at 30 months for *Eucalyptus* seedling lots obtained from Dongmen China project and grown at Peepekeo, Hawaii

SEED LOT	DIAMETER (in)	HEIGHT (ft)
D039	3.2	33.5
D048	4.3	36.4
DO67	3.8	34.1
DO140	3.9	36.1
DO142	3.6	33.8
D0141	3.5	32.8
DO149	3.1	30.2
D160	4.0	35.8
T.C.	1.9	21.0
AGXU	3.5	33.5
ARA2277	2.9	28.5
DO44	3.2	29.5
DO45	4.2	38.4
DO72	4.0	35.8
DO73	3.0	30.5
DO54	3.3	30.5
E. MICRO	2.0	21.6
ARA 2277	2.8	28.9
156-2	3.7	33.8

Some of the Brazilian clones were cut at about seven years age to provide vegetative propagation material. The shoots from the stumps will be propagated using both conventional and micropropagation techniques.

When enough propagation material is obtained, plot work can begin which will compare Brazillian clones to locally selected clones and the best seedling provenances. We anticipate that a preliminary evaluation for yield can be made on trees of 2 to 3 years of age.

The characteristics of a clone selected for biomass energy should include vigorous rooting of cuttings, rapid early growth, disease resistance, straight bole, self thinning branches, resistance to pests such as rose beatle, medium density, low bark percentage, high yield, and a high rate of coppice (regrowth). If selection is for hardboard or paper pulp additional quality factors will come in to play relative to the end products desired.

ECONOMICS OF BIOMASS PRODUCTION

Agricultural, harvest, and transport costs were used to determine the cost of delivery of biomass to a conversion facility. The dry biomass yields used were those obtained in the present study. Discounts were taken in consideration of expected mechanical harvesting losses relative to hand harvested experimental plots (25% discount), and for consideration of gross yields obtained experimentally versus net yields expected in a commercial operation (15%). Experimental yields and expected commercial yields for crops studied in HSPA experiments including those in the present study (marked with @) are given in **Table 19.** Included in **Table 19** is the recovered biomass for the Hawaiian sugar industry for the years 1986 to 1991. Recovered biomass from the sugar industry is the best benchmark for biomass yield potential, since the yields are among the highest obtained for any commercial crop. Dry biomass for the sugarcane crop was calculated from official sugar industry statistics and from unpublished reports in HSPA files and includes sugar, fiber, and dry molasses solids (refractometer solids). The values will slightly under estimate dry biomass owing to the presence of some insoluble dry matter not recorded as refractometer solids in the molasses.

For this study we have assumed that the biomass produced would be used as a fuel for the production of electricity. We have valued the fuel at the replacement cost of No.2 fuel oil priced at $32/bbl and have assumed that 1 bbl of fuel oil is the equivalent of one half ton of dry biomass. We realize that cheaper fuels such as No. 6 bunker oils and coal are available on some islands and that the value of biomass for electrical generation would be substantially diminished if these alternatives were used as the basis of comparison.

We have used the format of Hubbard and Kinoshita, 1993 to present the cost of biomass production on an annual and per ton biomass produced basis at the conversion site(**Table 20**). Costs would be substantially increased, especially for the grass crops, when the cost of preparation (moisture removal) is added. The values obtained vary from those of Hubbard and Kinoshita primarily owing to the use of different assumptions for land holding cost, G&A, and biomass yield. The estimated cost per ton of biomass produced varied from a low of $59/ton for unirrigated (rainfed) napiergrass (banagrass) to $103/ton for irrigated Leucaena. The cost of producing sugarcane biomass was estimated to be $86/ton in irrigated locations and $77/ton in rainfed locations (**Table 20**). Rainfed *Eucalyptus* was intermediate at $71/ton.

The cost per ton calculation is highly dependent on the yield of biomass obtained and there is considerable room for yield improvement especially for the tree crops. In addition sugarcane biomass yield can also be improved by selecting for high fiber canes and harvesting without burning. Costs per ton for biomass were calculated over a reasonable range of yields for the crops listed in **Table 21**.

Examples of the economics of biomass production using potential yield values for the crops are presented (**Table 22**). None of the crops studied produced enough yield to make electricity generation feasible based on current equivalent values based on alternative fuels including the highest value fuel, diesel oil.

Our recommendation is to find higher value uses for the biomass such as veneer in the case of wood biomass and medium density hardboard in the case of the grass biomass. Some potential may exist for the production of alcohol fuels from biomass if higher levels of conversion of cellulose and hemicellulose reported are demonstrated in commercial fermentation facilities. Higher efficiencies of conversion of biomass to electrical energy or liquid fuel will increase its value and perhaps make biomass-generated power a reality.

The biomass yields obtained in this study can also be used to determine the economics of production for other potentially higher value uses for biomass such as paper pulp, medium density hardboard, veneer and alcohol fuels.

Table 19. Experimental Biomass yields and Calculation of Expected Commercial Yield From HSPA Experiments (1982-1993)

Biomass Crop	Experimental Yield (ton/gross acre/yr)	Estimated Commercial Yield (ton/gross acre/yr)	Estimated Commercial Yield (ton/net acre/yr) *
	Yields from Current Project @		
Sweet sorghum (6 cult. av. 2 crops)	23.2	17.4	14.8
Sweet sorghum (MN1500, 2 crops)	32.7	24.5	20.8
Sorghum/sudangrass	17.6	13.2	11.2
Corn (Av. of 2 crops)	20	15.0	12.8
Alfalfa (Av. of 2 expt., 22 harvests)	11.8	8.9	7.5
Napiergrass (Av. 2 crops, 5 locations)	31.8	23.9	20.3
Napiergrass (Av. 7 crops , 1 location) @	19.6	14.7	12.5
Eucalyptus grandis, (close spacing) @	15.9	11.9	10.1
Eucalyptus urophylla, (close spacing) @	18.6	14.0	11.9
Acacia mearnsii (close spacing) @	17.1	12.8	10.9
Eucalyptus grandis (large plots, Mt. View) @	9.1	6.8	5.8
Eucalyptus urophylla (large plots Honokaa) @	14.2	10.7	9.1
Leuccaena leucocephala (large plots, Maui) @	11	8.3	7.0
Leucaena leucocephala, (large plots, Molokai) @	9.59	7.2	6.1
Eucalyptus urophylla (large plots, Kauai) @	7.81	5.9	5.0
Sugarcane current study average *** @	14.32	10.7	10.7
Sugarcane Maui (from HSPA variety test) ***	22.2	16.7	16.7
Sugarcane Ka'u (from HSPA variety test) ***	16.7	12.5	12.5
Sugarcane (5 locations, 2 harvests) ***	19.5	14.6	14.6
Commercial sugarcane (recovered biomass) ****			
1991			14.09
1990			14.17
1989			14.70
1988			15.15
1987			15.70
1986			15.52

* Exp. yield discounted by 25 %

** Conversion from gross to net acre requires an additional 15 % discount

***based on HSPA net acre

**** Includes sugar, fiber, and soluble molasses solids

Data obtained from HSPA files, HSPA Variety Reports, HSPA Energy Reports and reports to the DBED and GACC.

Table 20. Cost of Biomass Feed Stocks at the Conversion Plant

Modified from Hubbard and Kinoshita (1993) Investigation of Biomass for Energy Production on Molokai. (HNEI Report)

	Biomass Crop											
	Sugarcane Irrigated		Napiergrass Irrigated		Leucaena Irrigated		Sugarcane Rainfed		Napiergrass Rainfed		Eucalyptus Rainfed	
Cost Center	($/acre/yr)	($/ton)	($/acre/yr)	($/ton)	($/acre/yr)	($/ton)	($/acre/yr)	($/ton)	($/acre/yr)	($/ton)	($/acre/yr)	($/ton)
Landholding	100	6	100	6	100	10	100	7	100	7	100	12
Soil Preparation	53	3	27	2	5	1	53	4	27	2	40	5
Planting/Ratooning (Includes Nursery)	135	8	67	4	16	2	135	10	67	4	14	2
Weed Control	92	6	46	3	64	6	92	7	46	3	40	5
Irrigation	260	16	371	21	328	33	0	0	0	0	0	0
Fertilization	115	7	148	8	40	4	115	8	148	10	53	6
Other Field*	179	11	89	5	89	9	179	13	89	6	30	4
Harvesting	123	8	115	6	238	24	123	9	115	8	209	25
Hauling	155	10	180	10	36	4	155	11	180	12	40	5
G&A-Field **	135	8	114	6	92	9	95	7	90	6	57	7
Research	32	2	36	2	20	2	28	2	30	2	17	2
Total Delivered Cost	1379	86	1293	72	1028	103	1075	77	892	59	599	71
Cost /ton		**$86**		**$72**		**$103**		**$77**		**$59**		**$71**
Assumptions:												
Harvests per planted crop (No.)	1		7		4		1		7		1	
Harvests per year (No)	0.5		1.5		0.2		0.5		1.5		0.17	
Average Crop Age (mos)	24		8		60		24		8		72	
Dry Matter Yield (t/a/yr)	16		18		10		14		15		8.4	
Irrigation supply cost ($/1000 gal)	0.1		0.1		0.1		0		0		0	
Irrigation requirement (gal/acre/day)	6000		6000		5000		0		0		0	

* Other field costs include road maintenance, non crop weed control, security, etc.

** G&A calculated as 10% of total cost

Table 21. Calculation of Cost per Acre per Year and Cost per Ton at Varying Potential Levels of Biomass Production

Biomass Crop	Level of Biomass Production (Tons/Acre/Year)				
	5	10	16	20	25
Sugarcane (Irrigated) Cost per acre per yr	NA	NA	1379	1449	1535
Sugarcane (Irrigated) Cost per ton ($)			**86**	**72**	**61**
Sugarcane (Unirrigated) Cost per acre per yr	NA	982	1115	1194	1293
Sugarcane (Unirrigated) Cost per Ton ($)	NA	**98**	**70**	**60**	NA
Napiergrass (Irrigated) Cost per acre per yr ($)			1239	1305	1387
Napiergrass (Irrigated) Cost per ton ($)	NA	NA	**77**	**65**	**55**
Napiergrass (Unirrigated) Cost per acre per yr ($)	NA	NA	904	983	1081
Napiergrass (Unirrigated) Cost per ton ($)			**57**	**49**	**43**
Trees (Irrigated Leuacena) Cost per acre per yr	891	1028	1192	NA	NA
Trees (Irrigated Leucaena) Cost per ton ($)	**178**	**103**	**75**	NA	NA
Trees (Unirrigated Eucalyptus) Cost per acre per yr	530	679	856	NA	NA
Trees (Unirrigated Eucalyptus) Cost per ton ($)	**106**	**68**	**54**	NA	NA

Table 22. Biomass Production Economics Examples

	Biomass Crop			
	Unirrigated		Irrigated	
	Eucalyptus urrophyla	Sugarcane	Leucaena K636	Banagrass
Commercial Yield of Dry Matter (Tons/Acre/yr)	10	14	10	20
Production Per 5 Year Rotation (Tons/Acre)	50	NA	50	
Produc tion Per 2 Year Rotation (Tons/Acre)	NA	28	NA	NA
Production Per 4 Year Rotation (Tons/Acre)	NA	NA	NA	80
Production Cost Per Year ($/Acre/yr)	679	1075	1028	1305
Estimated Cost of Production Per 5 Year Rotation	3395	NA	5140	NA
Estimated Cost of Production Per 2 Year Rotation		2150		
Estimated Cost of Production Per 4 Year Cycle of 6 Harvests	NA	NA	NA	5220
Value of Dry Matter at Five Years ($)/Acre Based on:				
No. 2 oil $32/bbl*	3200	1792	3200	5120
No. 6 oil at $20/bbl	2000	1120	2000	3200
Coal at $20/ton	900	1008	900	1440

*One ton of dry biomass is equivalent to 2 bbl of oil or 0.9 tons of coal

SUMMARY AND CONCLUSIONS

This study compared the relative productivity of grasses and trees grown for the production of dry matter (biomass). Conversion of the biomass to electricity was the primary objective, although there are clearly other alternatives for biomass such as the production of wood chips for conversion to paper pulp or production of higher-value products such as manufactured lumber, medium density hardboard and veneer.

With the exception of the Honokaa, Hawaii site, grasses were more productive than trees at all locations. Trees averaged over all sites produced 9.2 t/a/yr compared to 13.8 t /a/yr for the grasses. At the three upland sites *E. urophylla* was the most productive tree species, while at the lowland sites *Leucaena leucocephala* was the most productive. The highest annual yield for a tree species in the large demonstration plot experiments was (14.2 t/a/yr) for *E. urophylla* at the Honokaa site. The highest yield for a grass species was 19.6 t/a/yr for napiergrass (banagrass) at the Hoolehua site. The accumulated yield of tree biomass produced by *E. urophylla* at 5 years at Honokaa was (71 t/a); the accumulated grass biomass produced by napiergrass in 4.3 years at Hoolehua was (84.3 t/a).

The major constraint to the use of biomass for electricity generation is that it has to compete with alternatives such as fuel oil, coal, and diesel oil. Until there is a substantial increase in oil and coal prices or more efficient conversion, it is unlikely that biomass, from either grasses or trees, will be used for electricity generation. Higher value non-fuel options for biomass such as the production of paper pulp, manufactured wood, and veneer require further analysis. The biomass yield and cost of production figures obtained in this study can also be used in the economic analysis of other potentially higher value products. Production of alcohol fuels from biomass using demonstrated commercial technology was also not found to be economically feasible (Roberts & Hilton, 1988); however, a reevaluation of the use and biomass for alcohol fuels will be needed if commercial scale demonstration of more efficient biomass conversion is successful.

Another constraint to biomass production from trees is the relatively low yield of currently available trees. To improve tree yields a breeding and selection program is required similar to that operated for sugarcane by the Hawaiian sugar industry. Selection of elite, potentially high-yielding trees was initiated in the current project. It is expected that considerably higher yields for trees will be obtained using these and other high yielding selections.

Sugarcane yields are already the highest in the world in Hawaii and it is not expected that yield improvement will increase yields more than the average 1 percent per year since 1909. Selection of sugarcane for high fiber to produce higher biomass yield would not seem advisable since the value of sugar is about six times greater than the value of fiber.

Production of electricity from the combustion of biomass trees and grasses grown without the production of more valuable co-products such as sugar, and value-added wood products, does not appear economically feasible in Hawaii at the current time.

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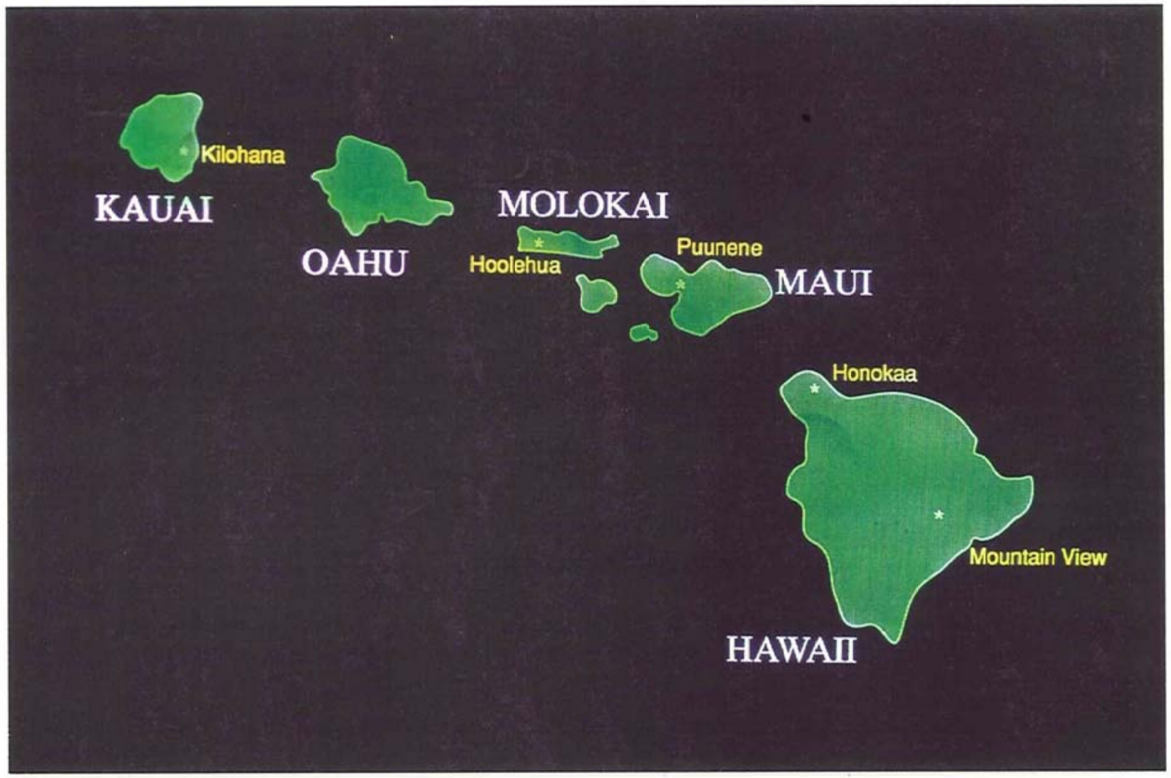
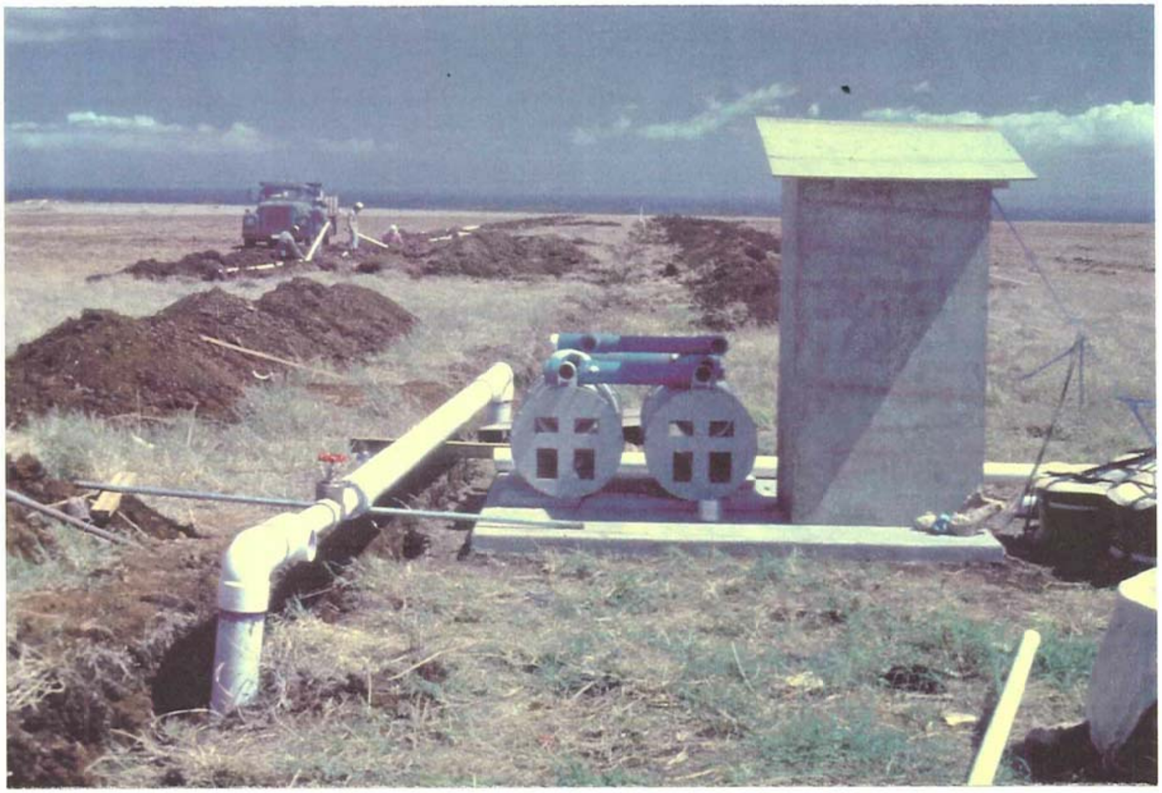


1. Locations of the 5 HSPA biomass sites.

2. Clearing the Mountain View Hawaii site.

3. Planting *Eucalyptus* seedlings into the mulch formed after the crushing operation at the Mountain View site.

4. Installation of drip irrigation at the Hoolehua, Molokai site.



5. Filtration and chlorination station at the Hoolehua, Molokai site.

6. Laying out the *Eucalyptus* seedlings for planting at the Hoolehua, Molokai site.

7. Ditch supplying irrigation water (mill water) to the furrow irrigation system used at the Puunene, Maui site.

8. Planting *Eucalyptus* seedling on the side of an irrigation furrow at HC & S on Maui.

9. *Leucaena* K636 showing severe border defoliation at the edge of a plot at the Puunene, Maui site.

10. *Casurina equisetifolia* (left) and *Leucaena* (right) at 18 months at the Puunene, Maui site.

11. Planting at the Kilohana, Kauai site.

11. Planting at the Kilohana, Kauai site.

12. Banagrass (*Pennisetum purpureum* cv. "banagrass") seed in shallow planting furrows with drip irrgation tubing placed between the lines at the Hoolehua, Molokai site.

13. *Leucaena* K636 at 9 months after planting at the Hoolehua, Molokai site.

14. *Leucaena* K636 at 18 months after planting at the Hoolehua, Molokai site.

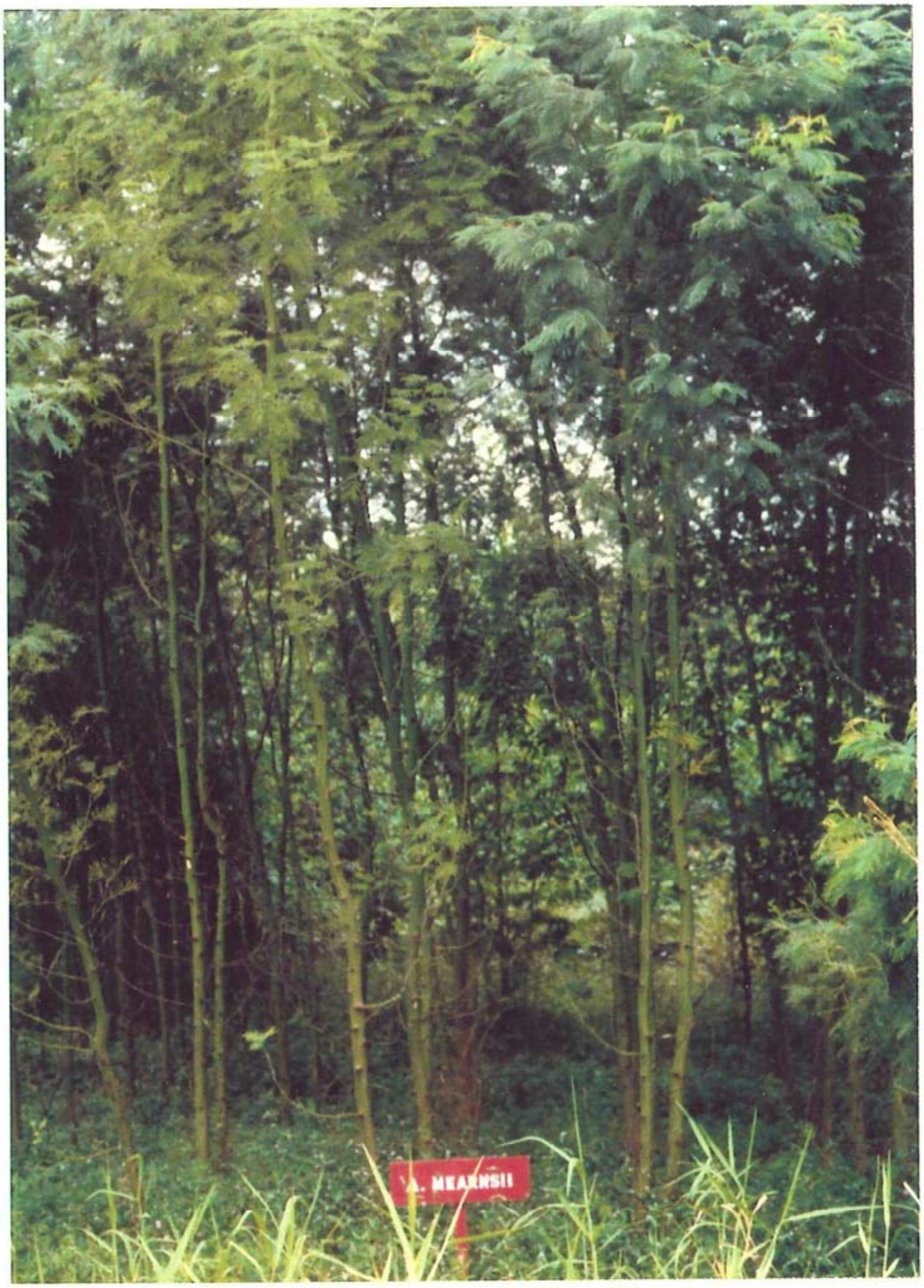
15. First ratoon of banagrass at the Hoolehua, Molokai site.

16. View of tree and grass biomass plantings at Hoolehua, Molokai site.

17. Cutting banagrass yield plots at the Hoolehua, Molokai site.

18. Weighing banagrass from yield plots at the Hoolehua, Molokai site.

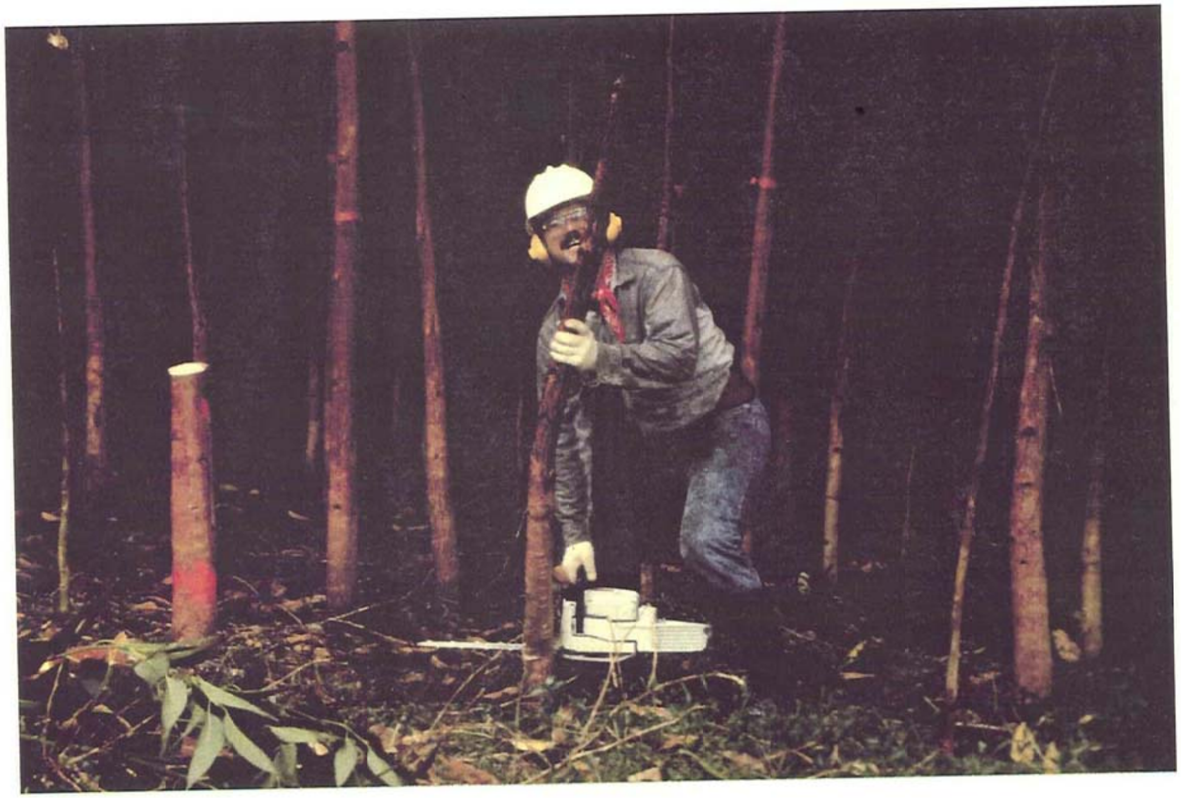
19. *Eucalyptus urophylla* at two years after planting at the Mountain View, Hawaii site.



20. *Acacia mearnsii*, the highest yielding tree in the closely spaced trials at the Kilohana, Kauai site.

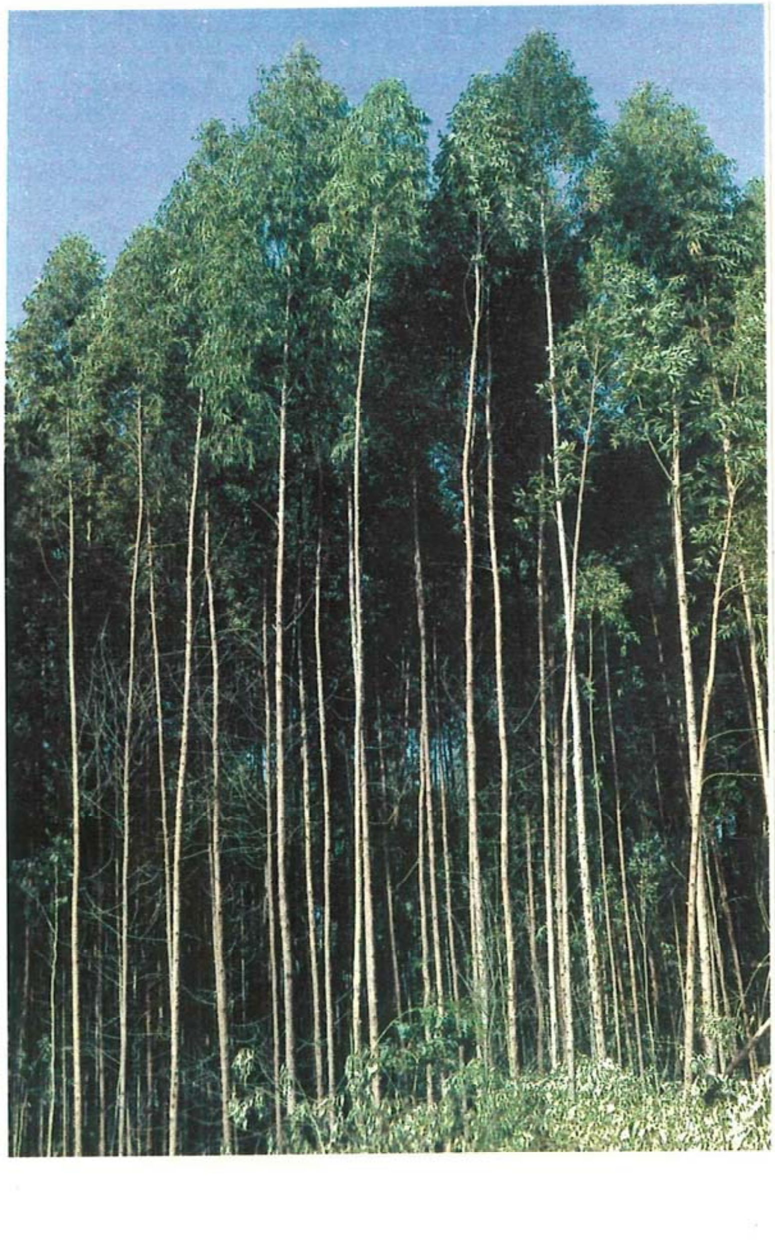
21. Mechanical harvest of the banagrass with with siclebar cutter at the Hoolehua, Molokai site.

22. Effect of the lack of fertilizer on the growth of *Eucalyptus grandis* at the Kilohana, Kauai site.



23. Harvest of two-year old *Eucalyptus* trees at the Mountain View, Hawaii site.

24. Clearing of harvested trees from the Mountain View, Hawaii site.



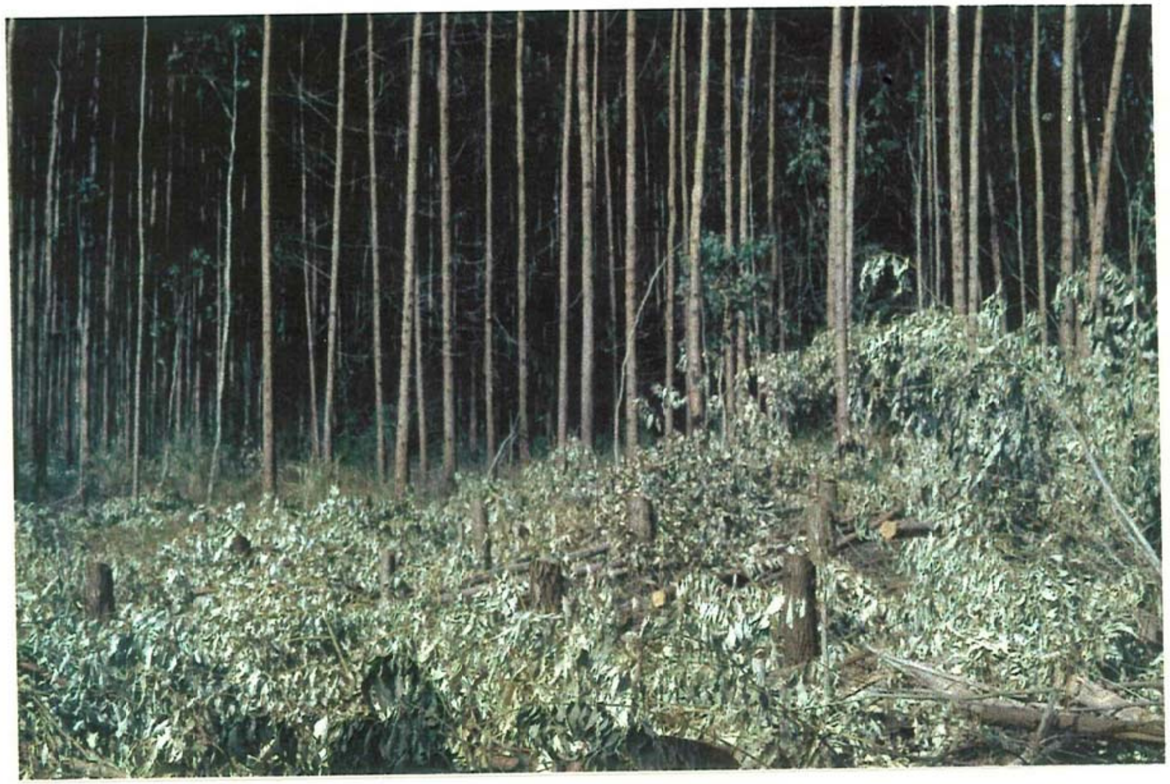
25. Five year old *Eucalyptus* stand at the Honokaa, Hawaii site.

26. Measuring a *Eucalyptus* tree in the 5 year harvest plot at the Honokaa, Hawaii site.

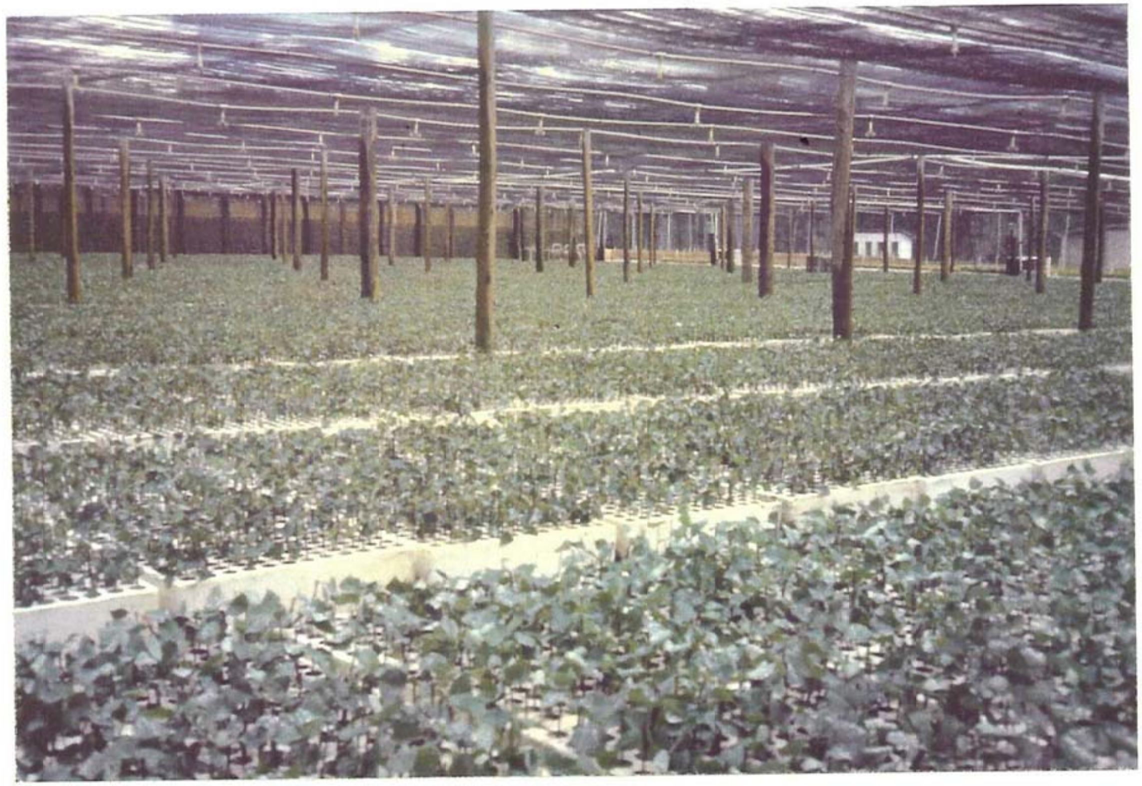
27. Cutting the five year plots using the BioEnergy Development crew at the Honokaa, Hawaii site.

28. Weighing 5 year old *Eucalyptus* at the Honokaa, Hawaii site.

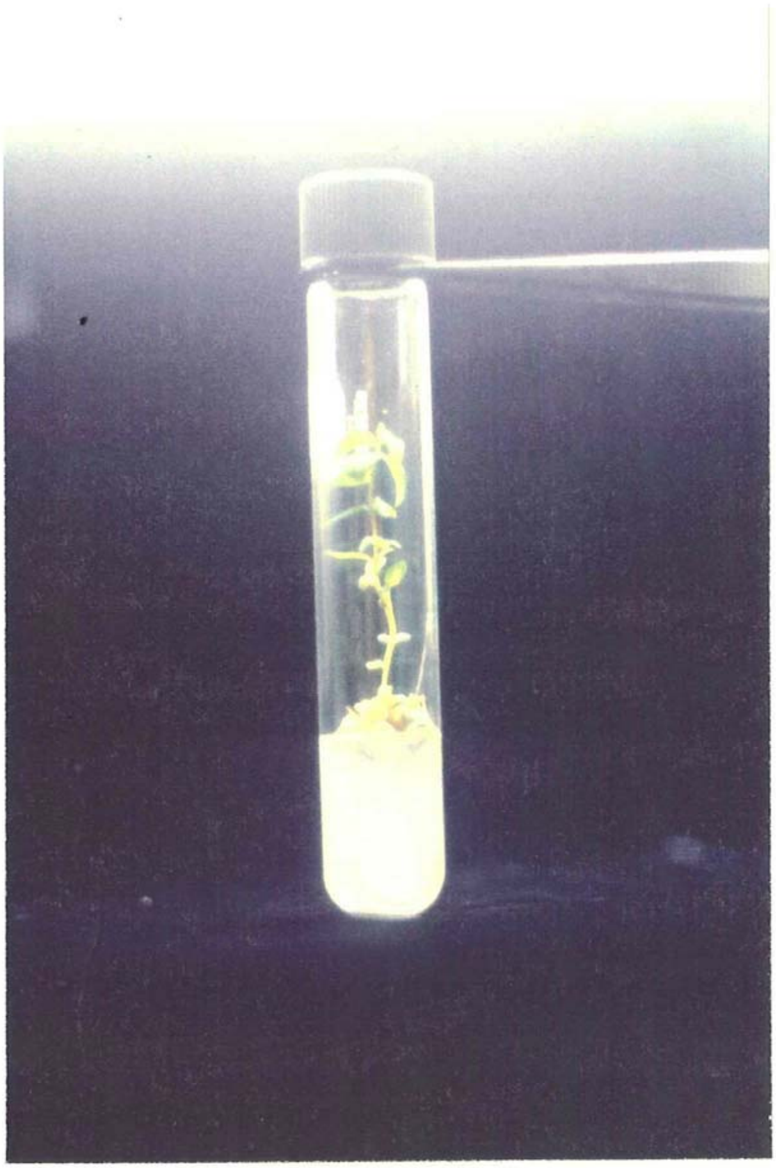
29. Stand of *Eucalyptus grandis* at the Honokaa, Hawaii site.



30. Cut harvest plot at five years after planting at the Honokaa, Hawaii site.



31. Large-scale vegetative propogation of *Eucalyptus* cuttings at Aracruz Cellulose Co. in Brazil.



32. Micropropagation of *Eucalyptus* at the HSPA. Plant is shown on rooting media and is almost ready for transplanting to the nursery.

33. Technique used in Brazil at Aracruz Cellulose Co. to reduce fungal contamination of micropopagation cultures. Logs from selected seedlings or clones are cut into sections and brought into the greenhouse where they sprout. The young shoots emerging from the logs are micropropagated.

34. A Eucalyptus seedling selected at 7 years after planting at wide spacing (3 x 3m) for clonal propagation at the Aracruz Cellulose Co., Espiritu Santo Brazil.

35. A 10 year old clonal stand of *Eucalyptus* at Aracruz Cellulose Co.

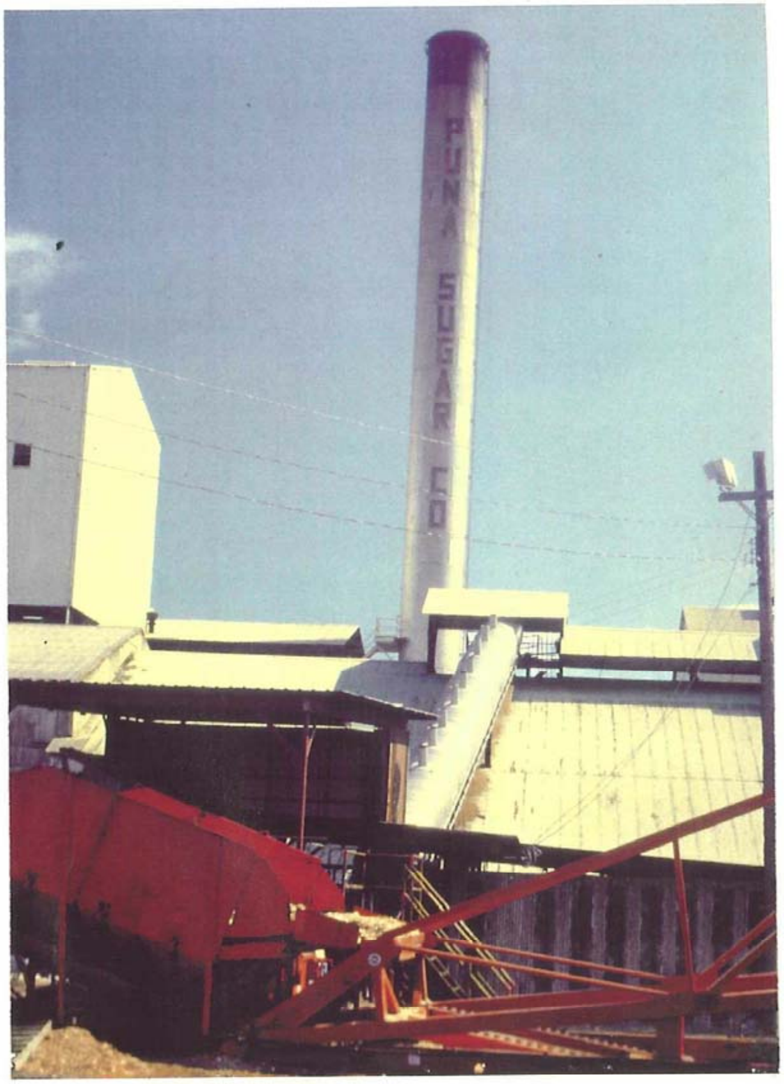
36. *Eucalyptus urophylla* seedling selected at two years after planting at close spacing (1 x 1m) for clonal propagation at Mountain View, Hawaii.

37. *Eucalyptus* stump being managed for production of vegetative cutting at Mountain View, Hawaii.

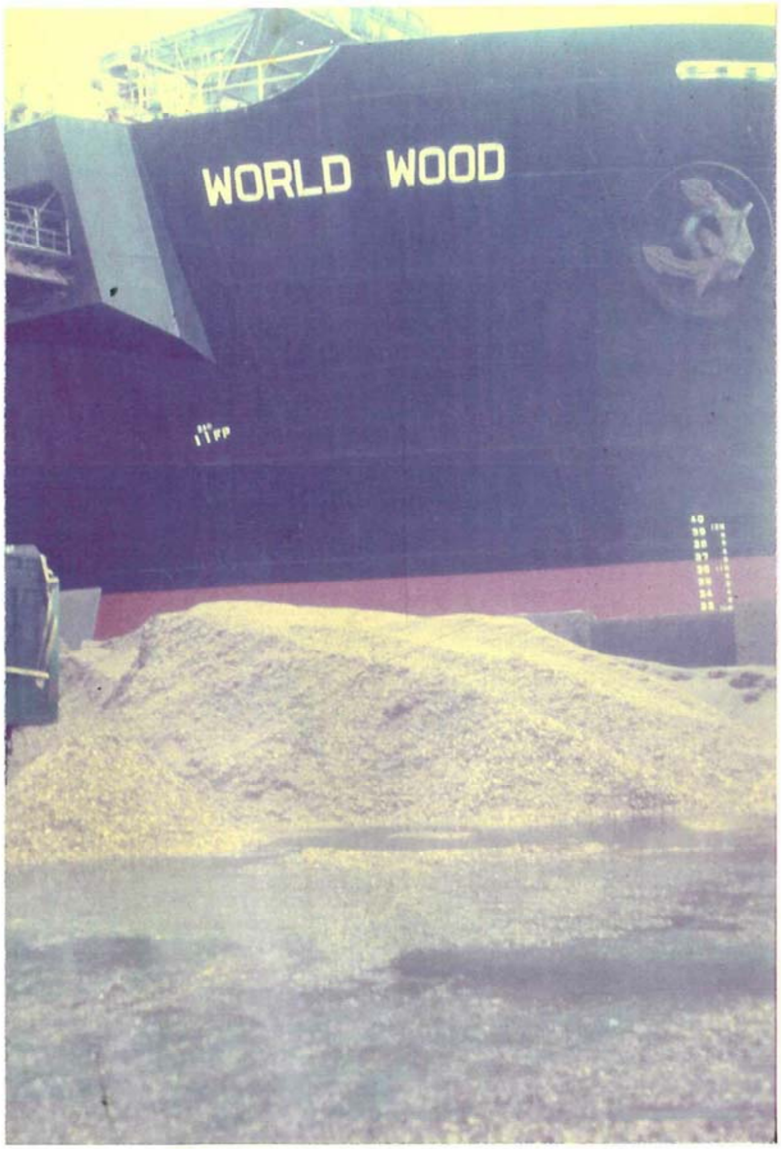
38. Crossing of *Eucalyptus* at Aracruz Cellulose Co.

39. Preparation of good agricultural land by BioEnergy Development Co. at Peepekeo, Hawaii, for the planting of selected provenances of *Eucalyptus* imported by the HSPA through an Australian AID program in China.

40. Planting of selected provenances of Eucalyptus imported by the HSPA. The planting was made by BioEnergy Development at their Pepeekeo experimental site.



41. A former Puna Sugar Co. biomass conversion facility at Keeau, Hawaii.



42. A wood chip vessel unloading in Taiwan.